

# Sharp Technologies as Applied to a Crew Transfer Vehicle (CTV)

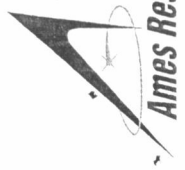
Presented by:  
Gelsomina Cappuccio

at University of California, San Diego

## Contributors:

Gary Allen, Jeff Bowles, Peter Gage, Ken Gee, David Kinney, Paul Kolodziej, Dean Kontinos, Mark Loomis, James Reuther, Cathy Roberts, David Saunders, Steve Smith, Bob Windhorst, Lily Yang, Jeff Bull, Joan Salute, Paul Wercinski, James Arnold, Sylvia Johnson, Fanny Zuniga, Susan Cliff, and Veronica Hawke of NASA Ames Research Center; and David Keese, Al Hodapp, and Mark Pilcher of Sandia

*April 10, 2003*

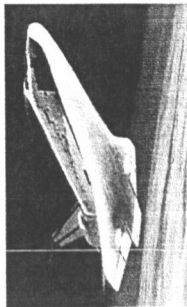


# NASA Entry Vehicles and Missions Supported by Ames



Ames Research Center

SPACE SHUTTLE



APOLLO



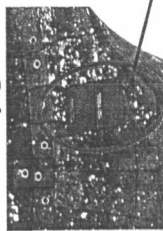
NASP



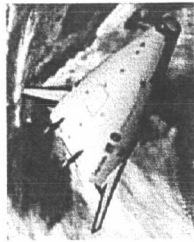
X-34



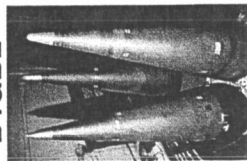
Shuttle Upgrades



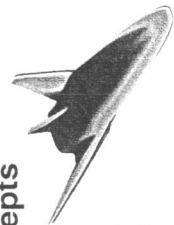
X-33



SHARP-B1&B2

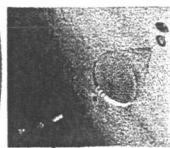


Sharp Body Concepts

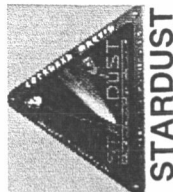


RLV SHUTTLE UPGRADES

PLANETARY  
• Mars 2005/07  
• Mars Sample Return  
• HEDS



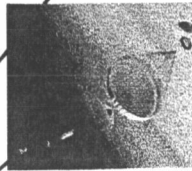
MER



STARDUST



MARS DS-2



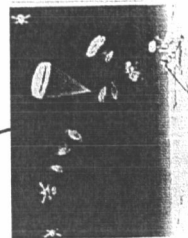
MARS PATHFINDER



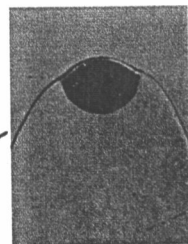
MAGELLAN



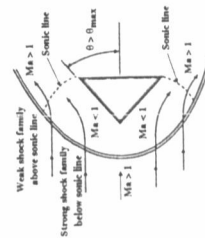
PIONEER-VENUS



VIKING

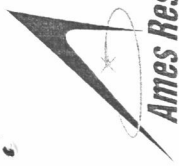


PAET



BLUNT BODY CONCEPT (H. Allen)



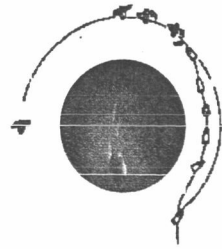


# Sharp Technology Impacts



- Enabled by Ultra-High Temperature Ceramics (UHTC's)
  - Temperature capability of 4000-5000°F, in contrast to the ~3000°F max limit for Shuttle
- Allows sharp leading edges for hypersonic vehicles
  - Tenths to hundredths of an inch radii, as opposed to Shuttle with radii measured in feet
- Enables sharp body vehicle concepts with low drag
  - Critical for airbreathing propulsion, rail launchers, and aero-maneuvering vehicle concepts, providing significantly reduced costs
- Allows high lift hypersonic vehicle designs
  - Providing aircraft-like maneuverability, including landings at standard airports, and enabling global cross range for greatly improved safety
- Eliminates entry communications blackout
  - Enhances GPS navigation with continuous communications, further improving safety and reliability
- Enables future safe, affordable aerospace vehicles

Aero-Maneuvering  
Concepts



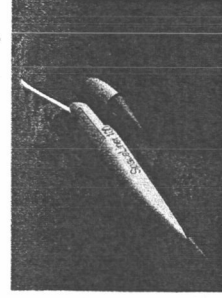
Commercial  
Global Express



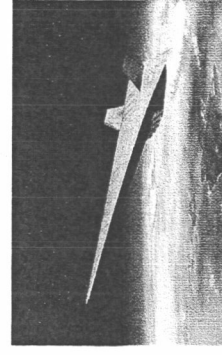
New Reusable  
Launch Vehicles

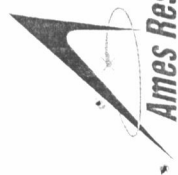


RBCC and Rail  
Launched Concepts



Future DoD  
Vehicles





Ames Research Center

# Ultra-High Temperature Ceramics (UHTC's)



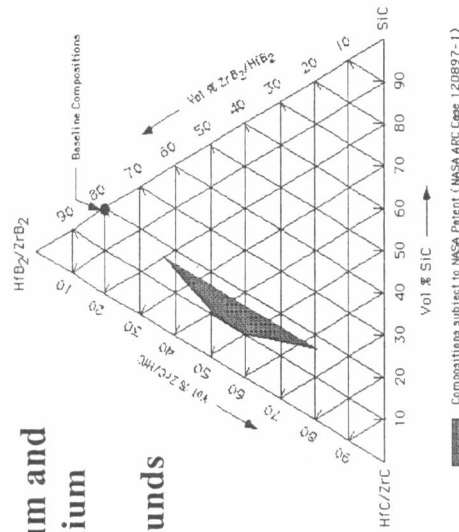
UHTC's have a unique combination of thermal and mechanical properties that enable their operation from room to *ultra-high* temperatures, including:

- Base material melt temperatures up to 7000°F
- Oxide melt temperatures up to 5000°F
- Flexural strengths up to 720 MPa
- Thermal Conductivities up to 104 W/m-K
- Thermal Expansion Coef as low as 4.2 ppm/K
- Moduli as low as 214 GPa

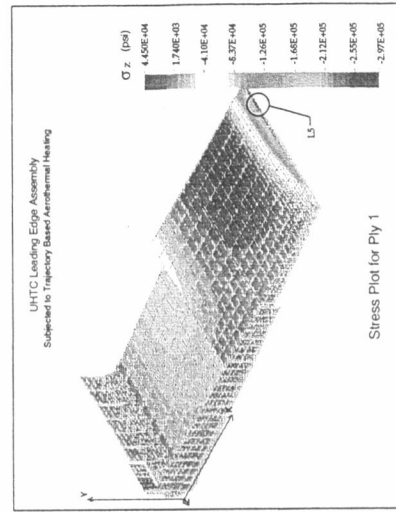
UHTC's form a surface oxidative and thermal barrier in-situ, providing fail-safe operation

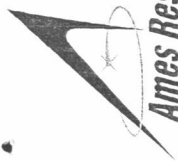


Hafnium and Zirconium based compounds

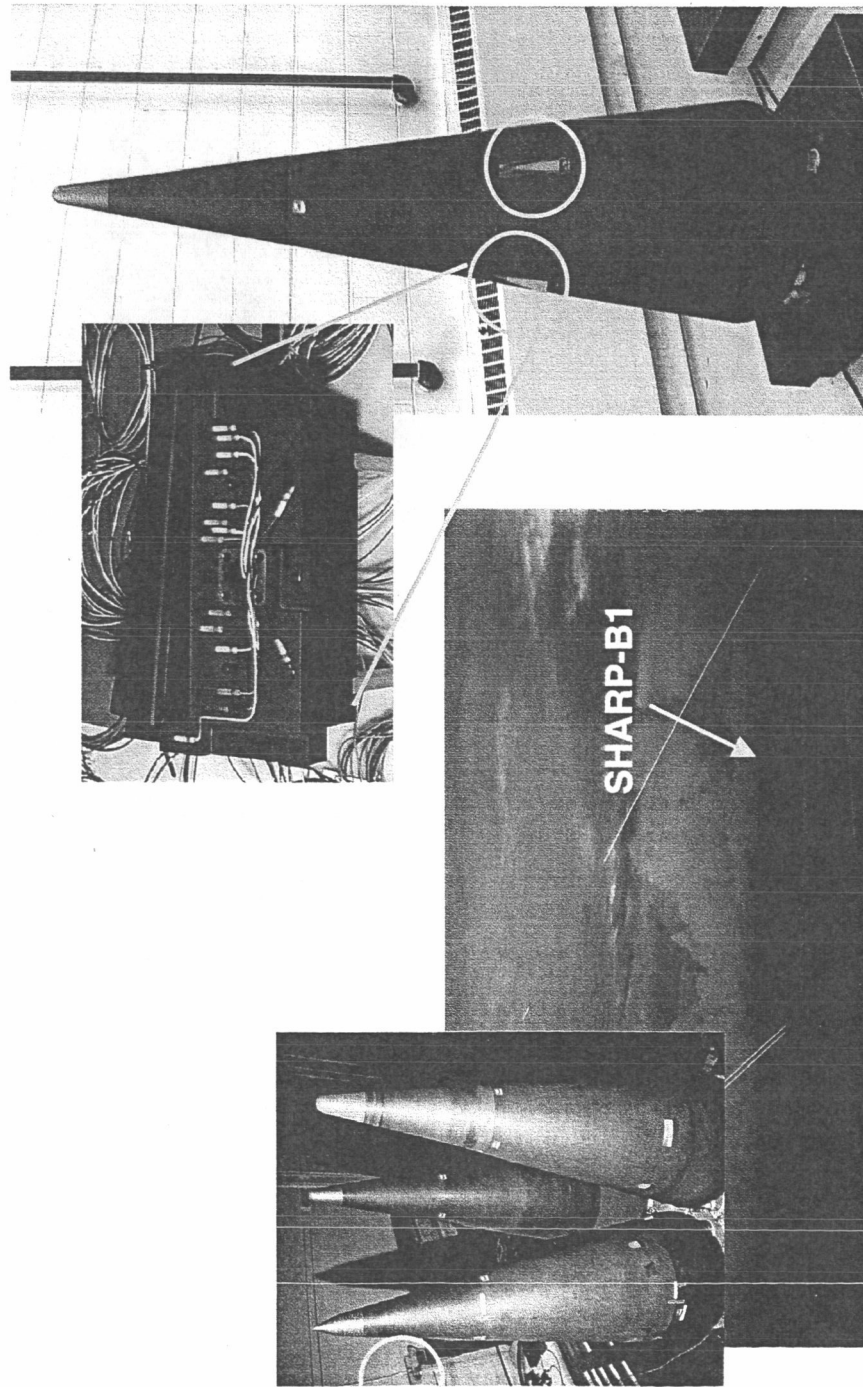


UHTC sharp leading edges can be designed to sustain in-flight thermal and aerodynamic loads





# SHARP\* Program Completed to Date



**SHARP-B2:**  
Successfully completed and flow in 21 months (Sept. 2000 flight)  
Objective: Verify UHTC sharp leading edge thermostructural performance  
Team: NASA ARC, MSFC, Sandia, SoRI, USAF, Materials and Machines, Paul Beckman Corp.

**SHARP-B1:** Successfully completed in 6 months (May 1997 flight)  
Objective: Verify UHTC sharp nosetip thermophysical performance  
Team: NASA ARC, Sandia, USAF, White Materials, Paul Beckman Corp.

*Sandia's involvement and contributions, and the support of the Air Force, have been key to the success of the SHARP program to date*



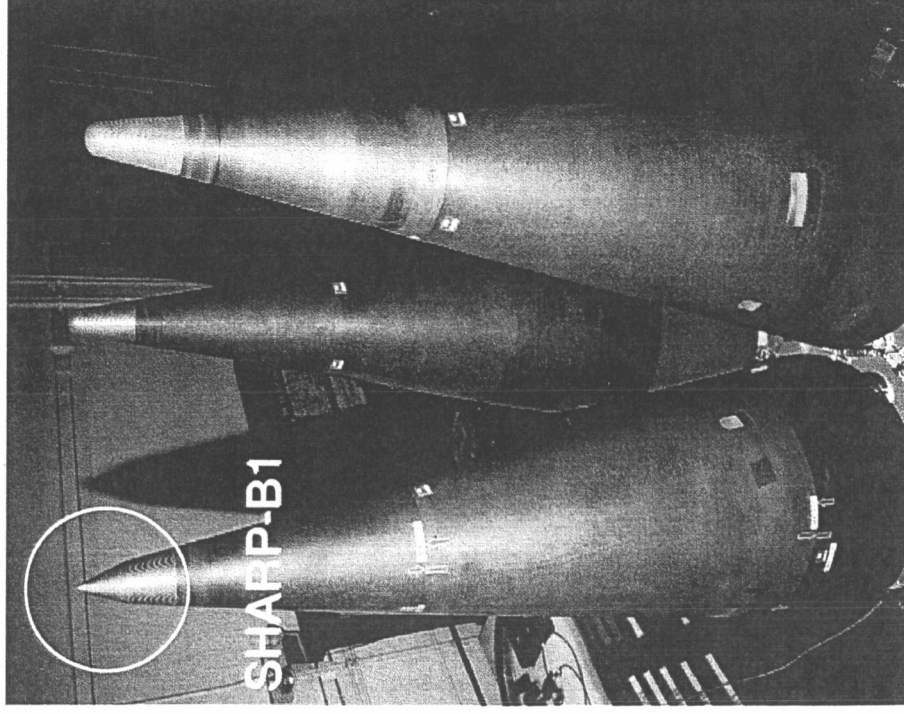
**Sandia National Laboratories**  
\*Slender Hypersonic Aerothermodynamic Research Probes



## SHARP-B1: May 21, 1997



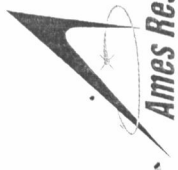
- UHTC first flight demonstration
  - Funded 1/97, flew 5/97!
  - NASA Cost \$1.2 M
  - Designed, built, tested, & flew .141" radius UHTC nosetip
  - Partnered with Sandia National Labs, USAF
  - Minuteman III launch
  - Instrumented UHTC nosetip on modified reentry vehicle
  - Design passed rigorous qualification testing and flight



# SHARP-B1 Flight Results Summary



- Nostip Material met/exceeded expectations
  - Ablation occurred after crossing aerothermal performance constraint, surface temps of +5000° F generated
  - No communication blackout, normal RF attenuation was reduced.



# SHARP-B1 Post-Flight Results & Recommendations

*Ames Research Center*



- Steady state analysis giving UHTC nosetip ablation limit corresponds well with measured flight performance, showing apparent UHTC ablation onset
- Discrepancy between predicted and measured transient nosetip temperatures not understood and requires further study
- Recommendations for further study:
  - Simulate the transient response of the SHARP-B1 nosetip at high altitude by DSMC/COSMOS.
  - Use this simulation for improving the rarefied flow correlations in PERFORM/COSMOS and reduce the discrepancy between the transient analysis and the flight data.
  - Perform a frequency analysis of the signal output between Event 2 and Event 3.
  - Use this analysis for correlating the output of the Tier 1 thermocouples to the Mk12A vehicle dynamics.
- Additional flight test, including recovery of UHTC components, should be pursued

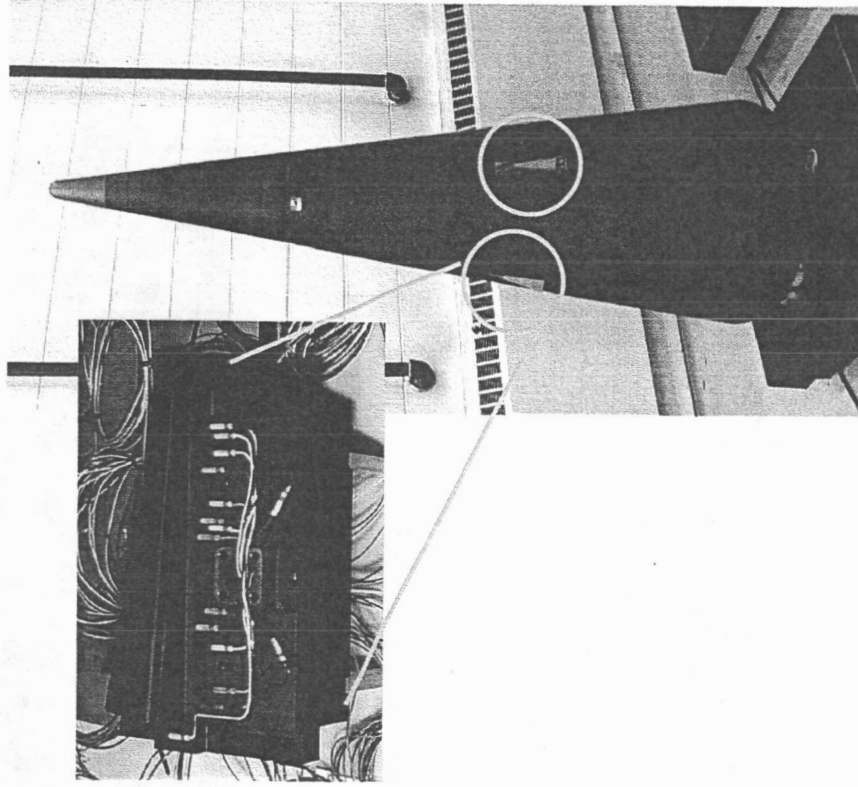




# SHARP-B2 Launch & Recovery Highlights



- Launched September 28, 2000 3:01 a.m. from VAFB.
- Tracked with 3 radar systems.
- Full retraction on strake #4 took longer than expected.
- Main chute malfunction caused vehicle to impact nearly 3X faster than expected, but minimal damage to strakes.
- 100% data collection on 140 channels.
- Vehicle recovered from a depth of 165 feet, approximately 500 feet from predicted impact point on October 1, 2000.



# SHARP-B2 Mission Scenario Sept. 28, 2000

(1) Deployment from  
Minuteman III

(2) Exoatmospheric  
mass ejection

(3) Reentry

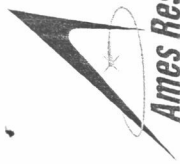
(4) Strake  
Retraction  
(Pair 1)

(5) Strake  
Retraction  
(Pair 2)

(6) Chute  
Deployment

(7) Soft Water Impact

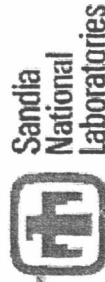
(8) Recovery  
and Return of  
SHARP-B2  
for Analysis



# SHARP-B2 Strake Response Highlights



- Recorded material temperatures were significantly below predictions
  - Similar low measured temperatures occurred with B1
  - Boundary layer/rarified flow/instrumentation effects being investigated to determine cause
- Thermal structural fractures occurred in the strakes in flight:
  - All four HfB2/SiC strake segments encountered multiple fractures
  - Two of the four ZrB2/SiC strake segments encountered fractures
  - None of the four ZrB2/SiC/C segments fractured
- High defects levels in the materials (particularly for the HfB2/SiC strake segments) believed to have at least contributed to the fracturing



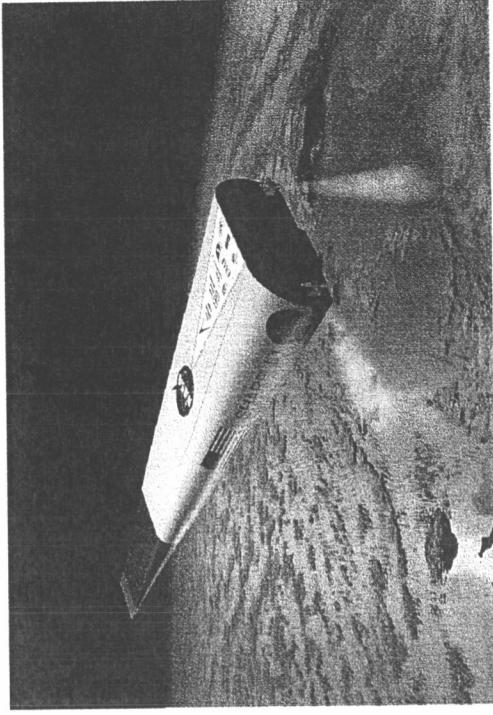


# SHARP Program Yet to Be Accomplished/Funded

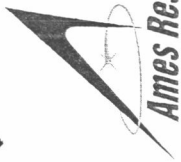


- SHARP-L1

- Demonstrate key technologies for operable sharp body vehicles:
  - Sharp UHTC leading edge assembly & acreage TPS
  - Novel lifting vehicle design and flight control
  - Landing/recovery systems
- Schedule: 36 months from authority to proceed
- Team members: ARC, Sandia, Air Force, Industry



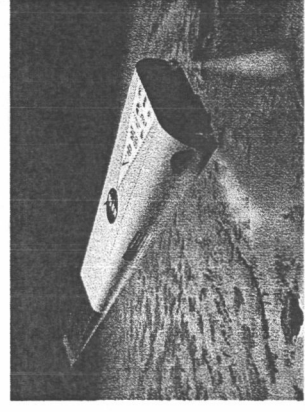
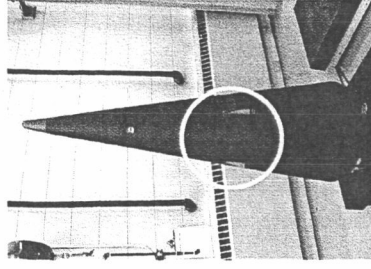
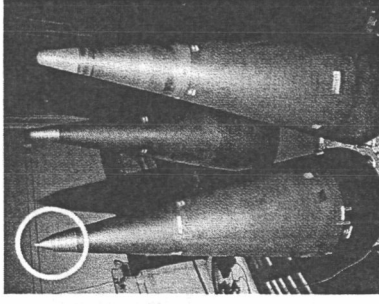
- Flight Scenario
  - Launched off of a Pegasus-XL, or other available boost asset
  - Mach 23+ re-entry
  - Flight into the Western Pacific Missile Test Range
  - Mid-air, intact recovery (Johnston Island recovery one option)



## Summary of SHARP Program



- SHARP-B1
  - Funded (\$1.2M) from discretionary reserves at the direction of HQ, Code R (Col. Gary Payton)
  - Successfully flew on May 21, 1997, six months after authority to proceed
- SHARP-B2
  - Awarded (~\$6M) under the first cycle of the MSFC Future-X program
  - Designed, fabricated, completed systems testing on budget and schedule (18 months), and successfully launched and recovered in September, 2001
- SHARP-L1
  - Initial development study completed under Spaceliner 100 program (~\$2M)
  - Estimated program for flight hardware design, fabrication and flight testing ~\$50M
  - Currently working continued UHTC ground development (have brought materials fabrication capability in-house), and sharp body systems studies under NASA 2nd Gen (SLI) and 3rd Gen (ASTP) RLV development programs



Sandia  
National  
Laboratories



# Ames SHARP CTV Architecture Study Plan



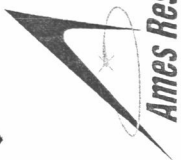
## Products

- Vehicle Concepts and Analysis (Include Performance, Mass, Trajectory, Reusability, Safety)
- Identify Key Trades and Sensitivities
  - L/D and cross-range/aborts
  - Subsonic landing and handling qualities
  - Vehicle mass/scale
  - SHARP/UHTC trades
- Mature RLV Analysis and Design Capabilities for 2nd Gen.
- Documentation of Study Results

## Schedule

- 9-Month Study, Finished October 2000.

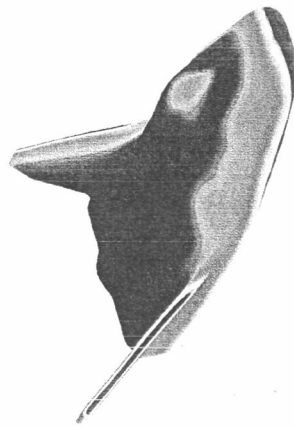




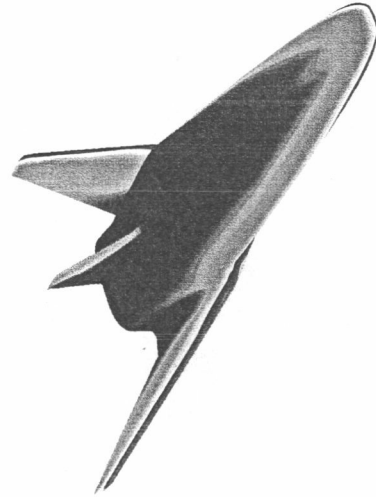
## NASA Ames CTV Mission Studies



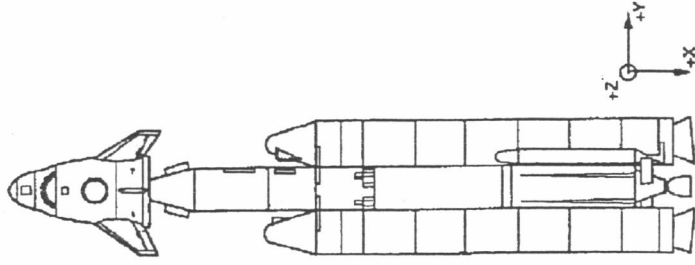
- Enter Orbit from Atop an Expendable Launch Vehicle
- Carry 8 Crew and 2 Pilots with Full Life Support for Multiple Days in Orbit
- Dock with International Space Station (ISS) for Crew Transfer
- Return from Orbit and Land on a Hardened Runway
- Survive a Range of Intact Ascent Aborts
- Fully Reusable TPS and Complete Vehicle Systems



**HL-20**



**SHARP-V5**



**HL-20 Ascent Stack**



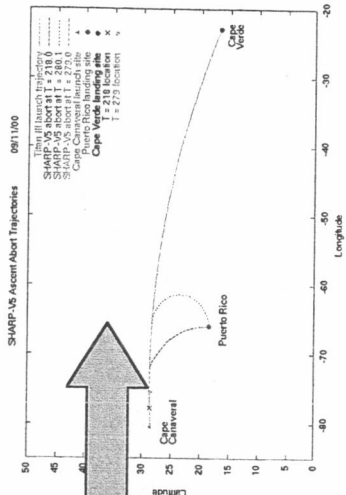
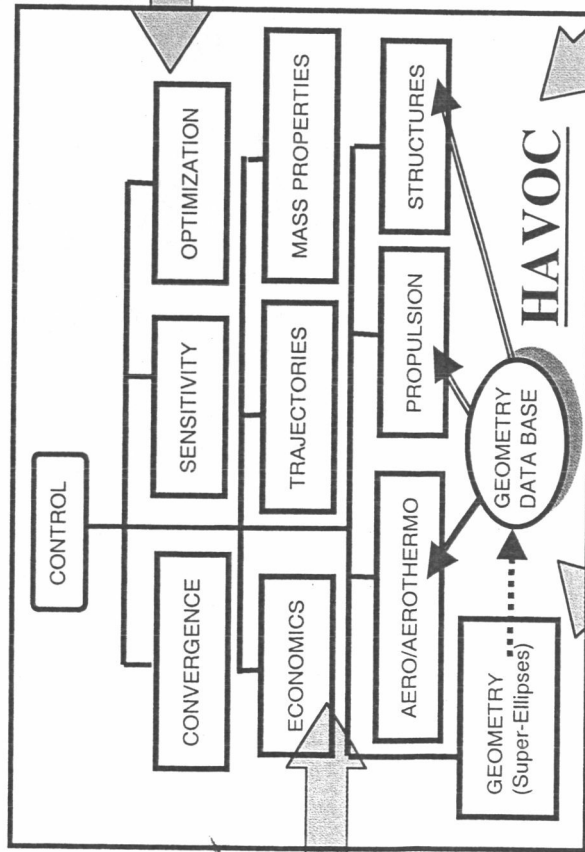
# HL-20 Chosen for Tools Validation



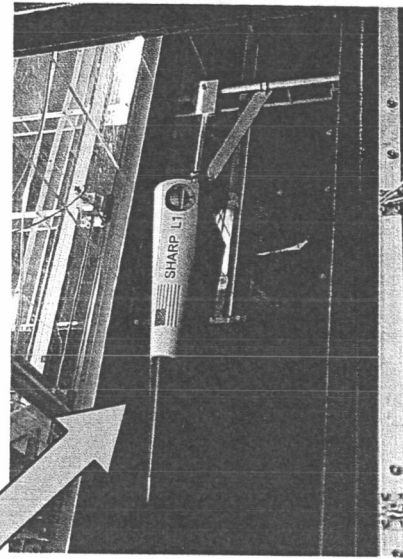
*Ames Research Center*

- **HL-20 Studied at NASA LaRC in Late 80s and Early 90s**
  - Multi-year, dedicated division effort
- **Extensive Results Published, Notably a Dedicated JSR Volume (1993)**
- **Rationale for Using HL-20**
  - Study results are recent, well documented, and fairly complete
  - Similar "CTV" design requirements
- **Use of HL-20 Results by Ames CTV Team**
  - As tool validation resource with comprehensive data
  - As solid comparison vehicle designed without SHARP technologies

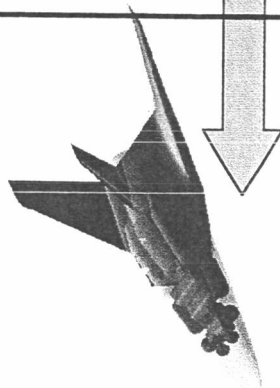
# Vehicle Sizing and Closure Process



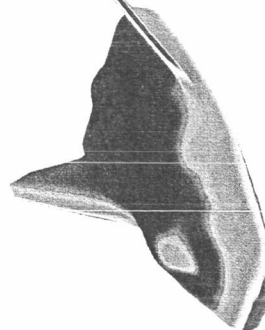
## Trajectory Optimization & Abort Analysis



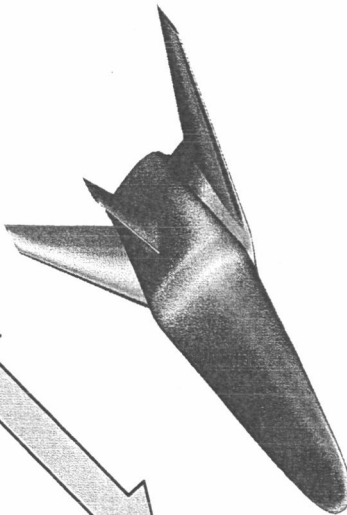
## Wind Tunnel Testing



## RAM



## CFD Analysis



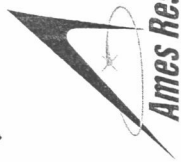
## HAVOC



# HAVOC Design Methodology



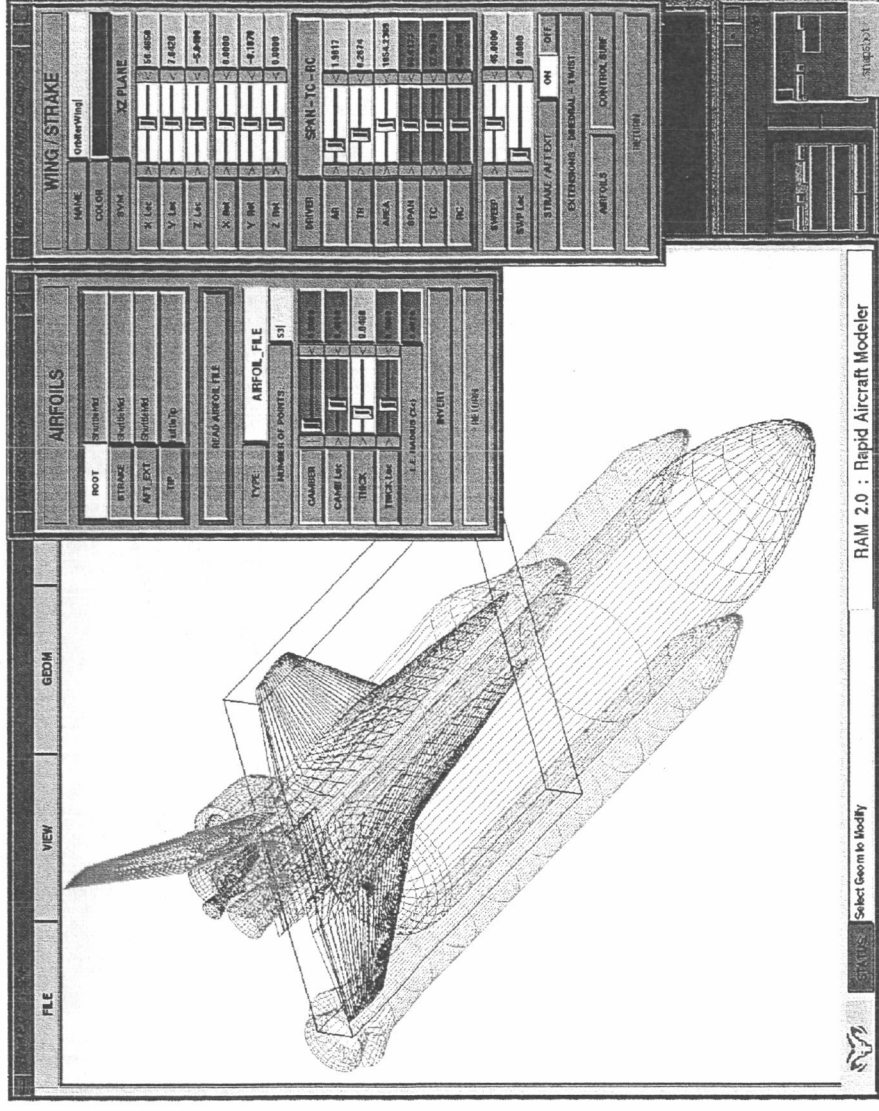
- Approach uses conceptual level spacecraft systems analysis and synthesis code HAVOC (Hypersonic Air Vehicle Optimization Code).
- Analysis Sequence includes:
  - Configuration Layout in RAM
  - HAVOC grid development from RAM layout
  - HAVOC aerodynamic and aerothermal database development, supplemented with low and high speed CFD data, and low speed wind tunnel.
  - Iterative HAVOC runs to establish vehicle closure for mission.

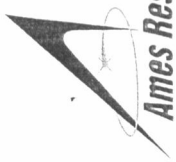


# RAM - Rapid Aircraft Modeler

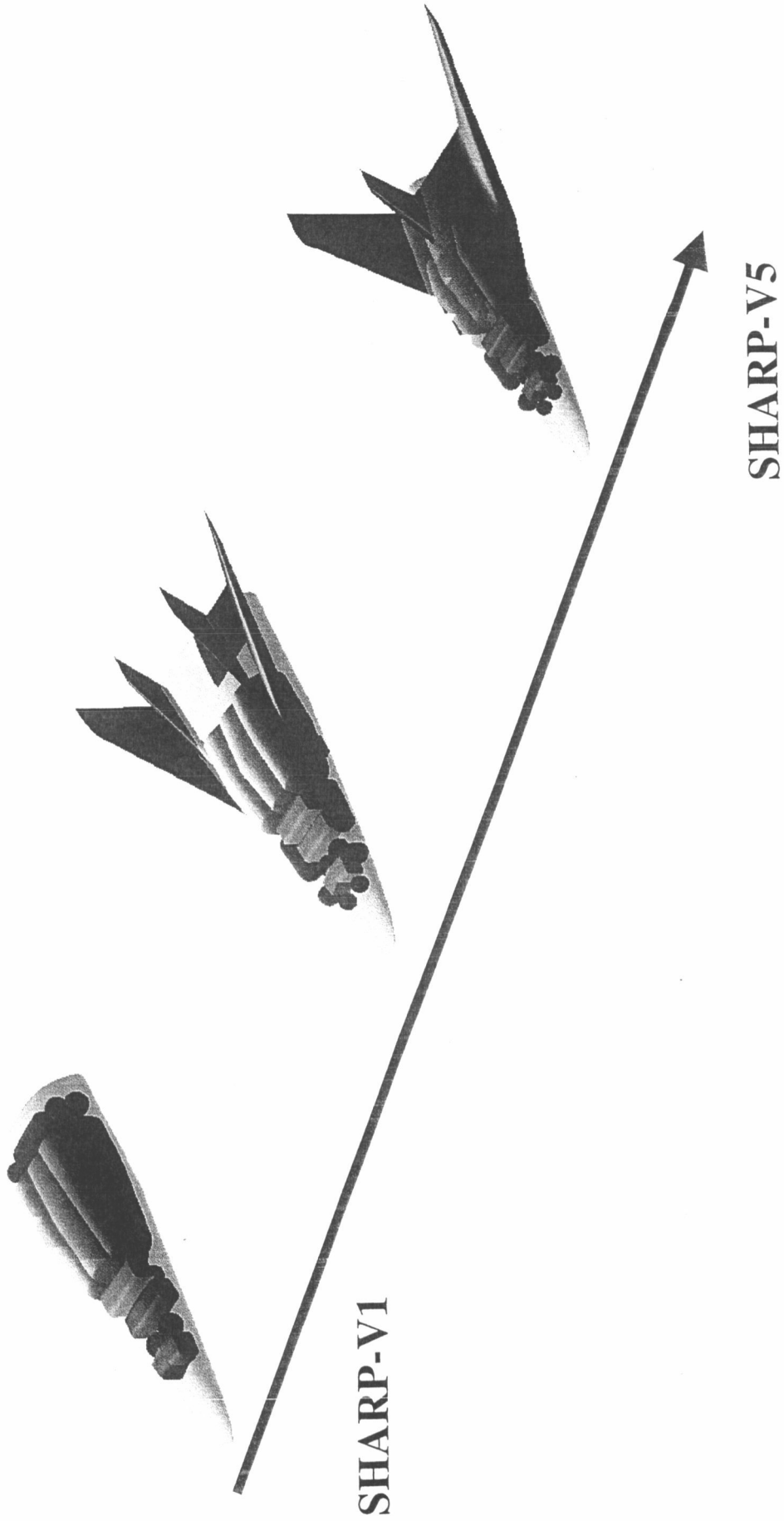


- Parametric Based
- Real Time GUI
- Components:
  - Wings
  - Fuselages
  - Engines
  - Inlets
- Import Background:
  - Images
  - Geometries
- Current Uses
  - Create and verify geometry for conceptual designs (HAVOC, ACSYNT...)
  - Calculation of wetted areas and volumes
  - Generate geometry for more detailed analysis codes (FLO107-MB, TIGER, GASP...)



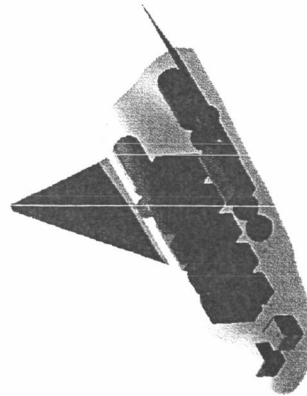
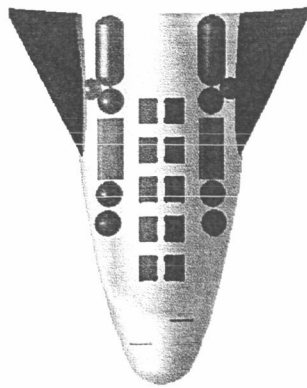


# Configuration Development

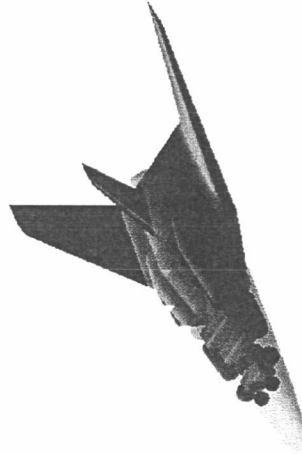
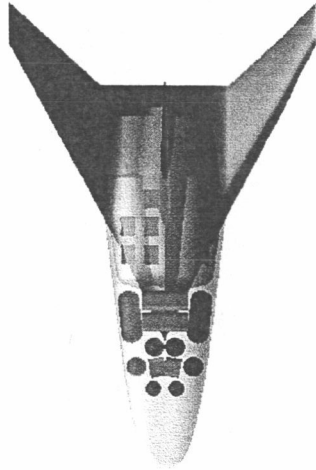




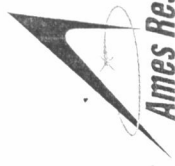
# RAM Models



HL-20

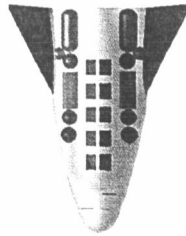
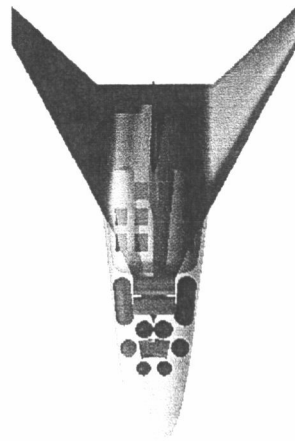


SHARP-V5



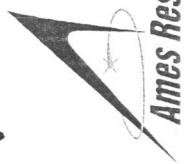
# Configuration Characteristics

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Re-Entry Weight, lbs	24517	25504
Empty Weight, lbs	20021	21000
Airframe Weight	8056	8766
Propulsion	1370	1436
Fixed Equipment	10595	10805
Payload/Crew	3771	3771
Consumables	726	726
Acreage TPS lbs/sqft avg	1.3	1.74*
Body length, ft	28.6	36.6
Wetted Area, sqft	935	1486
Re-entry W/S, psf	66.9	50.1
Re-entry CG	54%	57%
Hypersonic L/D	1.35	2.2

\*Preliminary results, body only.

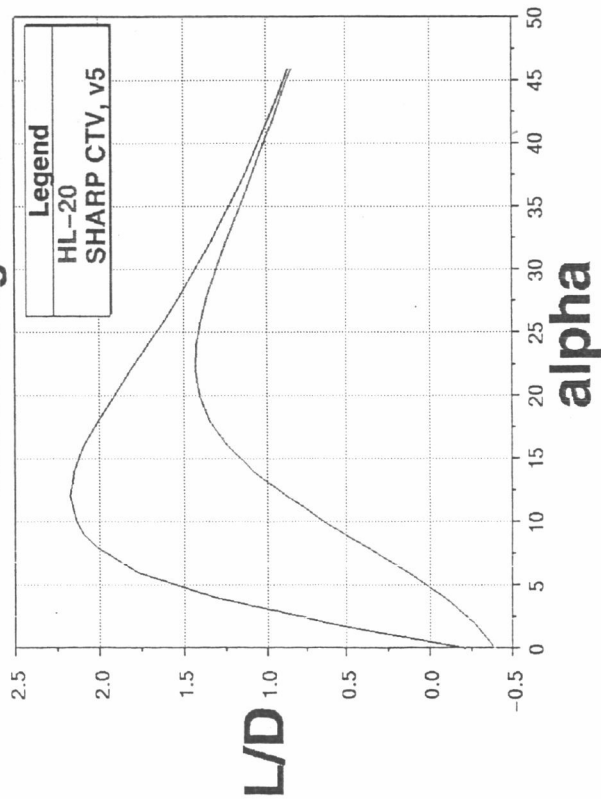


# HAVOC Newtonian Aerodynamics

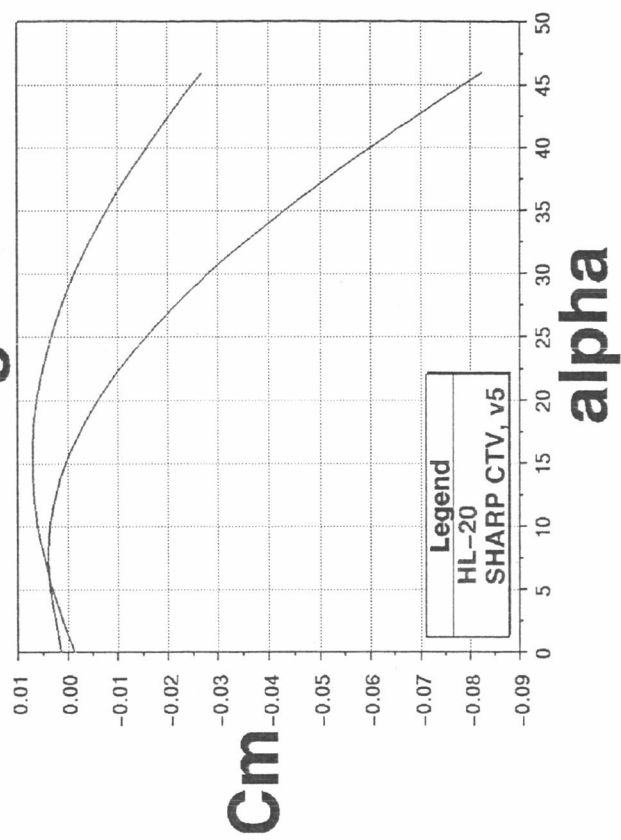
Ames Research Center HL-20 and SHARP-V5, Mach 25,  $Q=10$  psf



Lift to Drag Ratio

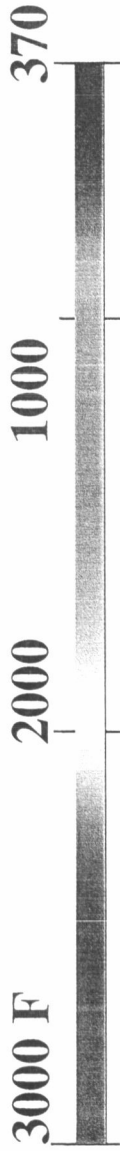


Pitching Moment

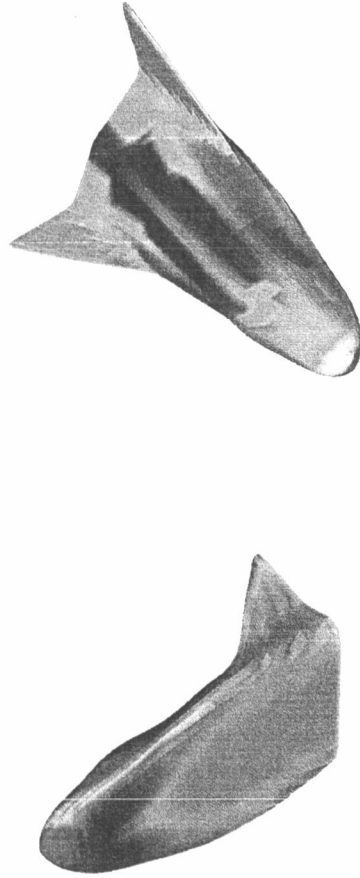


# Laminar Peak Heating Points

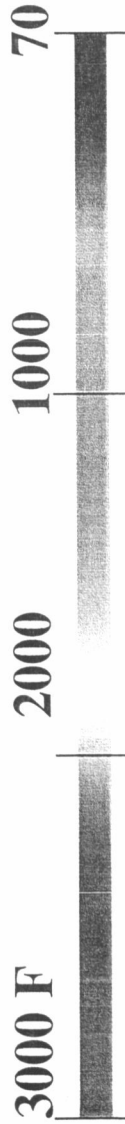
## HAVOC Results



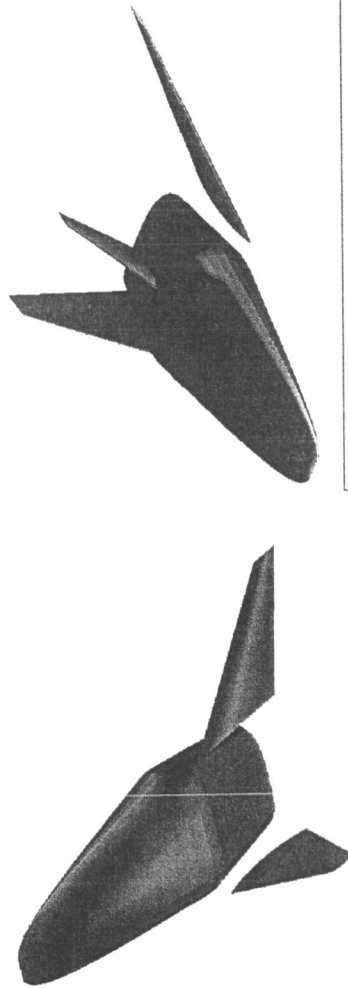
### Peak Laminar Heating Point



Mach 25  
240 kft  
Alpha = 30  
Q = 29 psf



### Peak Laminar Heating Point



Mach 25  
220 kft  
Alpha = 12.5  
Q = 72 psf

Note: SHARP CTV-v5 results do not include UHTC/ACC nose region.

# TPS Sizing



- **TPS sizing based on aerothermal environment**
  - TRAJ optimized trajectory used along with HAVOC aerothermal database
  - 1 D, unsteady analysis of TPS/structural lay up for 2500 body points
  - Convection + Radiation + Wall Conduction are balanced
  - TPS is sized to meet an interior wall temperature constraint (350 F)
- **HL-20 TPS sized and compares well with results presented in JSR 1993**
- **SHARP-V5 TPS sized**
  - Investigated Various TPS Systems
    - All Tile systems vs. Tile and Blanket Systems
    - Acreage TPS choice driven by both temperature and allowable TPS thickness
  - UHTCs Used Only on Sharp Nose Region
    - UHTC and ACC integration and design not completed
    - Aerothermal environment is within APC of UHTC and ACC



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# SHARP-V5 TPS/Structural Lay Up



nose, chines, flaps,  
wing leading edge



0.1" ACC

6" Gap

LI-2200

0.02" RTV

0.09" AL-2219

max. temperature  
2500 °F



0.1" TUFI

AETB-12

0.02" RTV

0.0625" GP Face Sheet  
(GP: Graphite Polyimide)

0.5" GP Honeycomb

0.0625" GP Face Sheet

6" Gap

1.0" Q-Felt

0.02" RTV

0.09" AL-2219

x > 26'



0.027" outer sheet  
(Astro-Quartz)

**Q-felt** (microquartz)  
0.011" inner sheet  
(E-glass)

0.02" RTV

0.09" AL-2219

AFRSI  
Blanket

- UHTCs Used at Nose Tip
- Integration with ACC not Completed

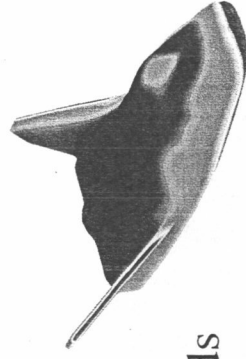


- **GASP for Hypersonic Aero and Heating**

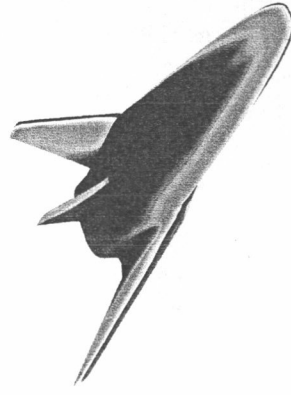
- Validated against HL-20 published data
- Provides Anchoring for Engineering Aero and Heating Methods

- **Multi-block/Parallel NS for Low Speed**

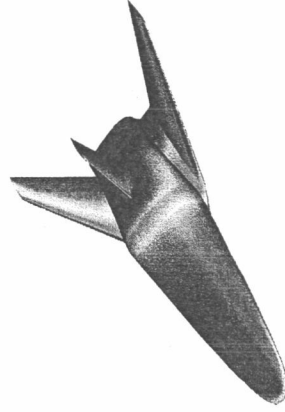
- Validated Against HL-20 Published Data
- Provides Landing Aerodynamic Database
- Provides Method of Obtaining Control Effectiveness
- Fast Turn-Around (~ 15 Minutes per N-S Solution)



**Mach 18 GASP Solution**  
**5 species air**  
**Fully catalytic wall**



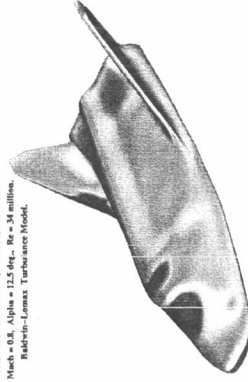
**Mach 23.8 GASP Solution**  
**5 species air**  
**non-catalytic wall**



**Navier-Stokes Solution**  
**Mach = 0.8, Alpha = 12.5 deg., Re = 34 mil.**  
**Baldwin-Lomax Turbulence Model**

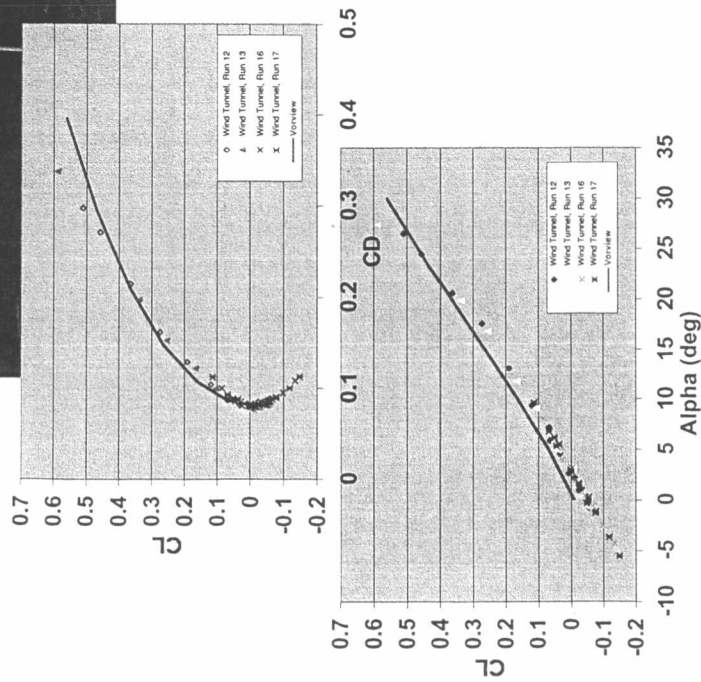
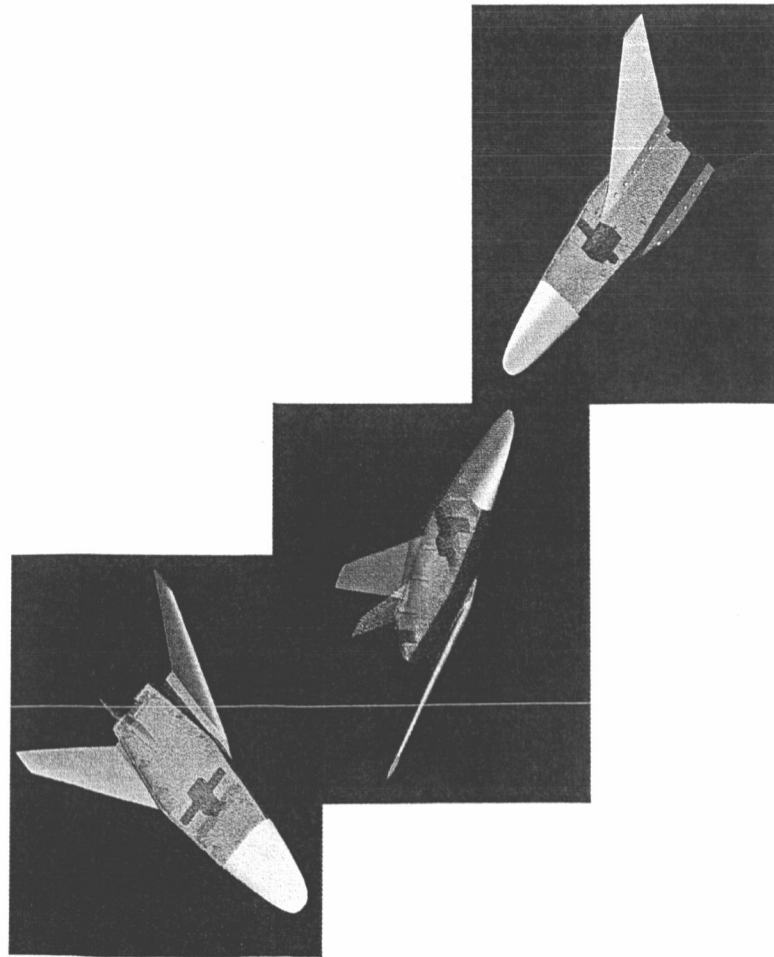
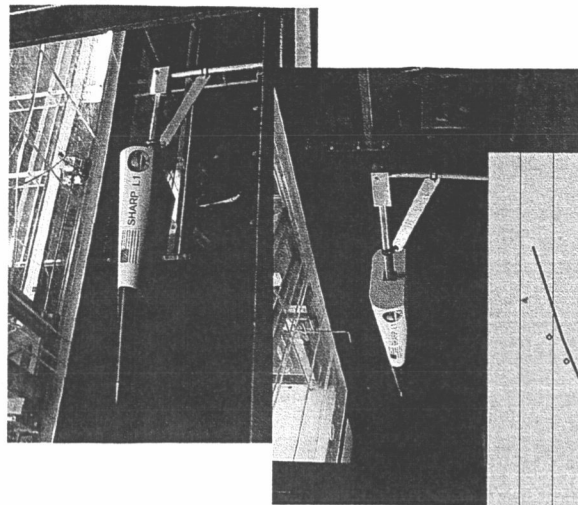
**Navier-Stokes Solution**  
**Mach 0.3, Alpha 10. Deg. Re = 60 mil.**  
**Baldwin-Lomax Turbulence Model**

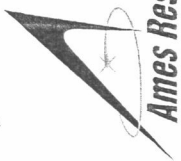
HL-20 Navier-Stokes Solution  
Mach = 0.8, Alpha = 12.5 deg., Re = 34 million.  
Baldwin-Lomax Turbulence Model.



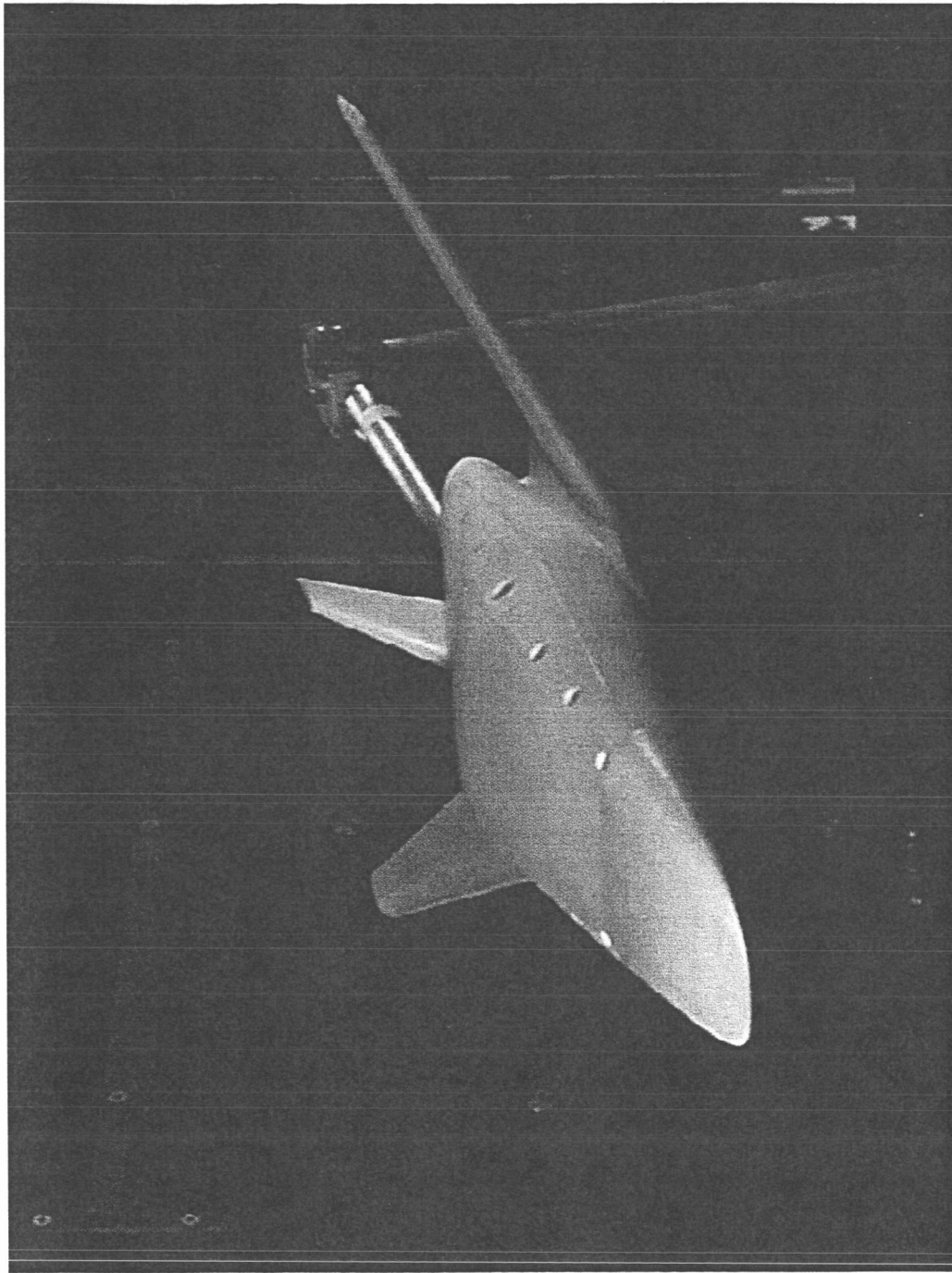
# Wind Tunnel

- Low Speed Wind Tunnel Testing Performed on L1 Vehicle
  - Data used to anchor codes to aid in development of CTV-V5
- Low Speed Model for CTV-v5 being fabricated

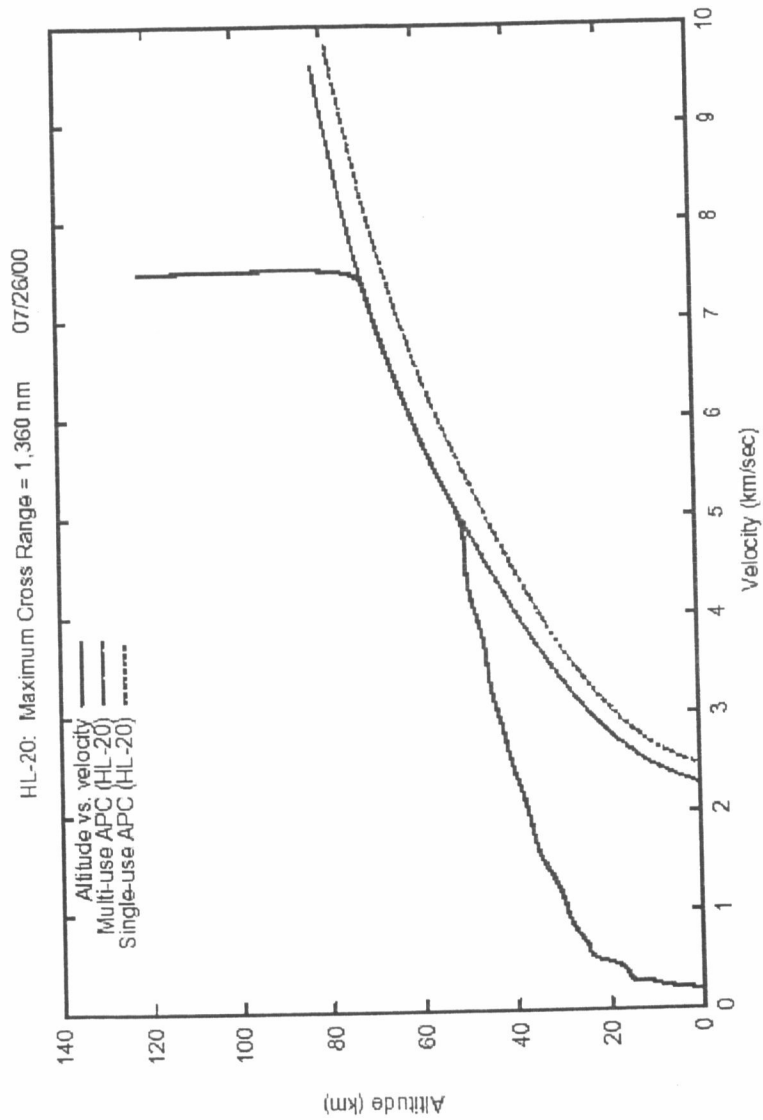




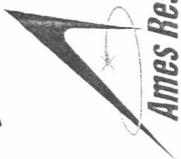
# SHARP CTV, v5



- Curve in (Velocity, Altitude) Space
- Drop Below  $\Rightarrow$  Too Fast / Too Low / Overheat



Need to Generate Lift  
to Stay Above APC

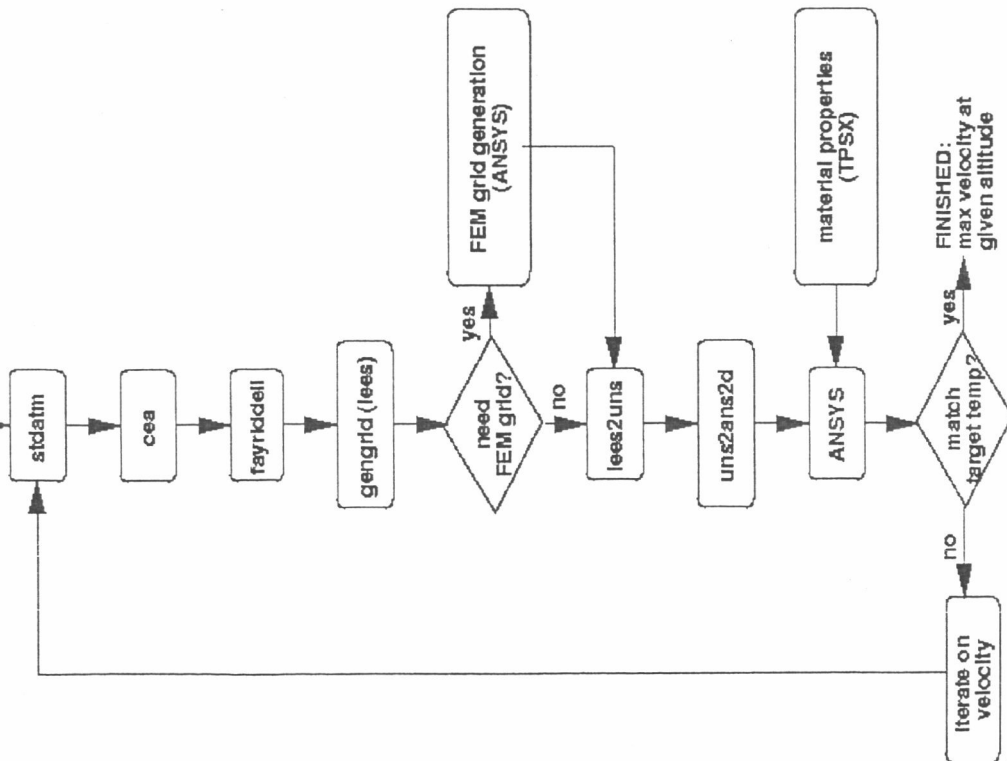


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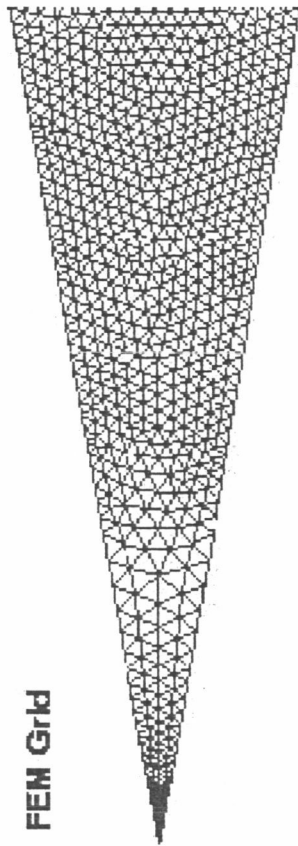
# UHTC Aerothermal / Thermal Analysis APC Development



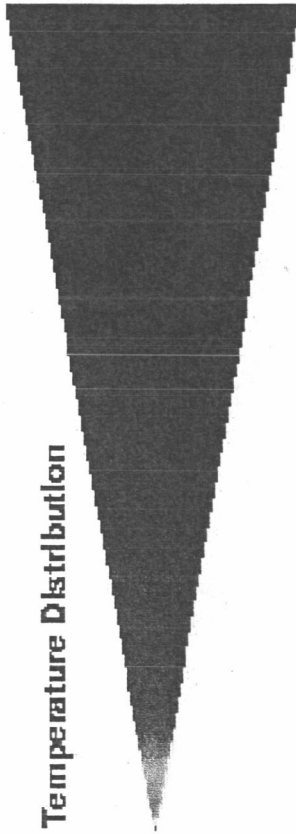
GIVEN:  
altitude, nose radius, wedge half angle, velocity guess



FEM Grid

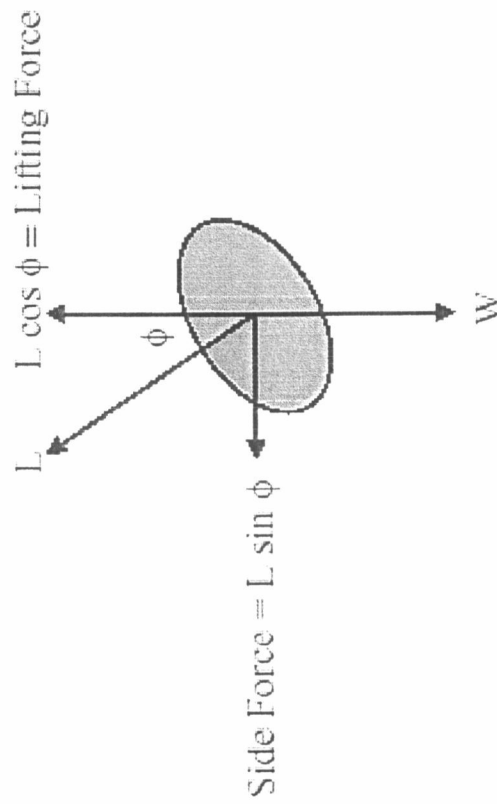


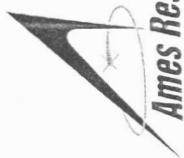
Temperature Distribution



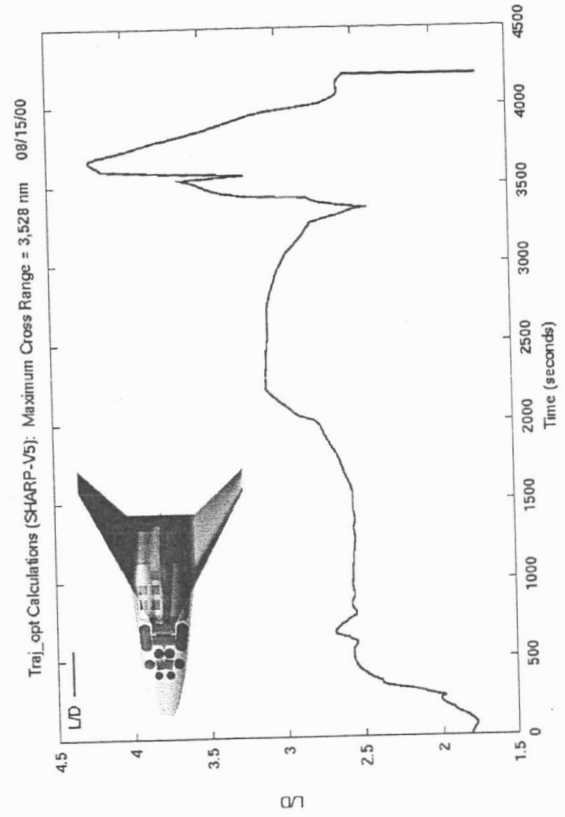
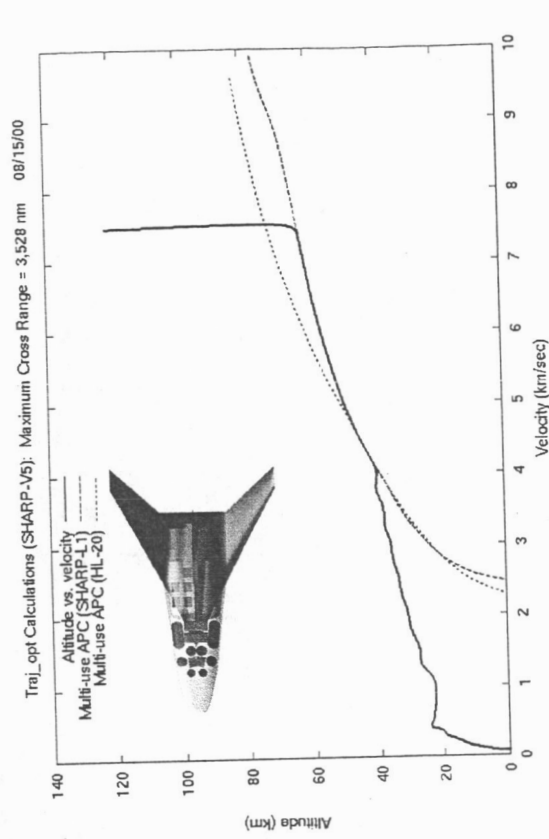
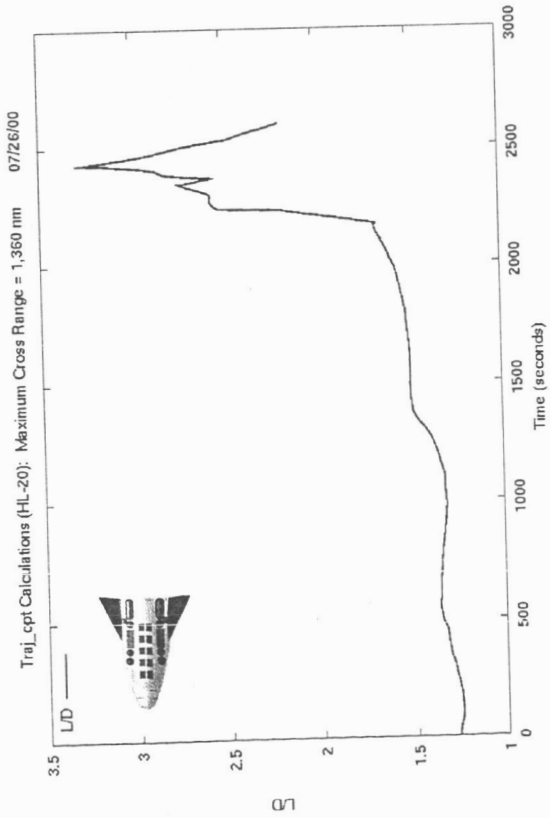
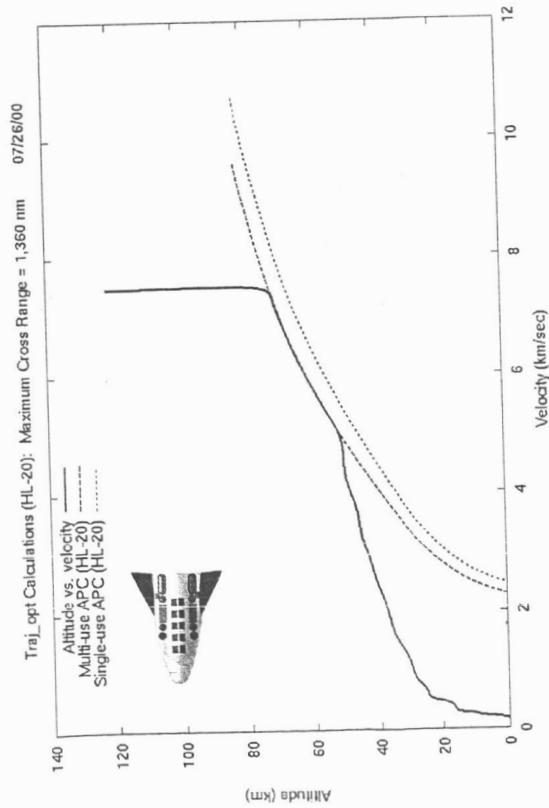
## NEED ENOUGH LIFT TO STAY ABOVE THE APC – NO MORE

- Excess Lift Allows More Bank  $\Rightarrow$  More Cross-range
- Excess Lift Allows Lower  $\alpha \Rightarrow$  Fly Closer to Best L/D





# Max Cross-Range Trajectory Optimization





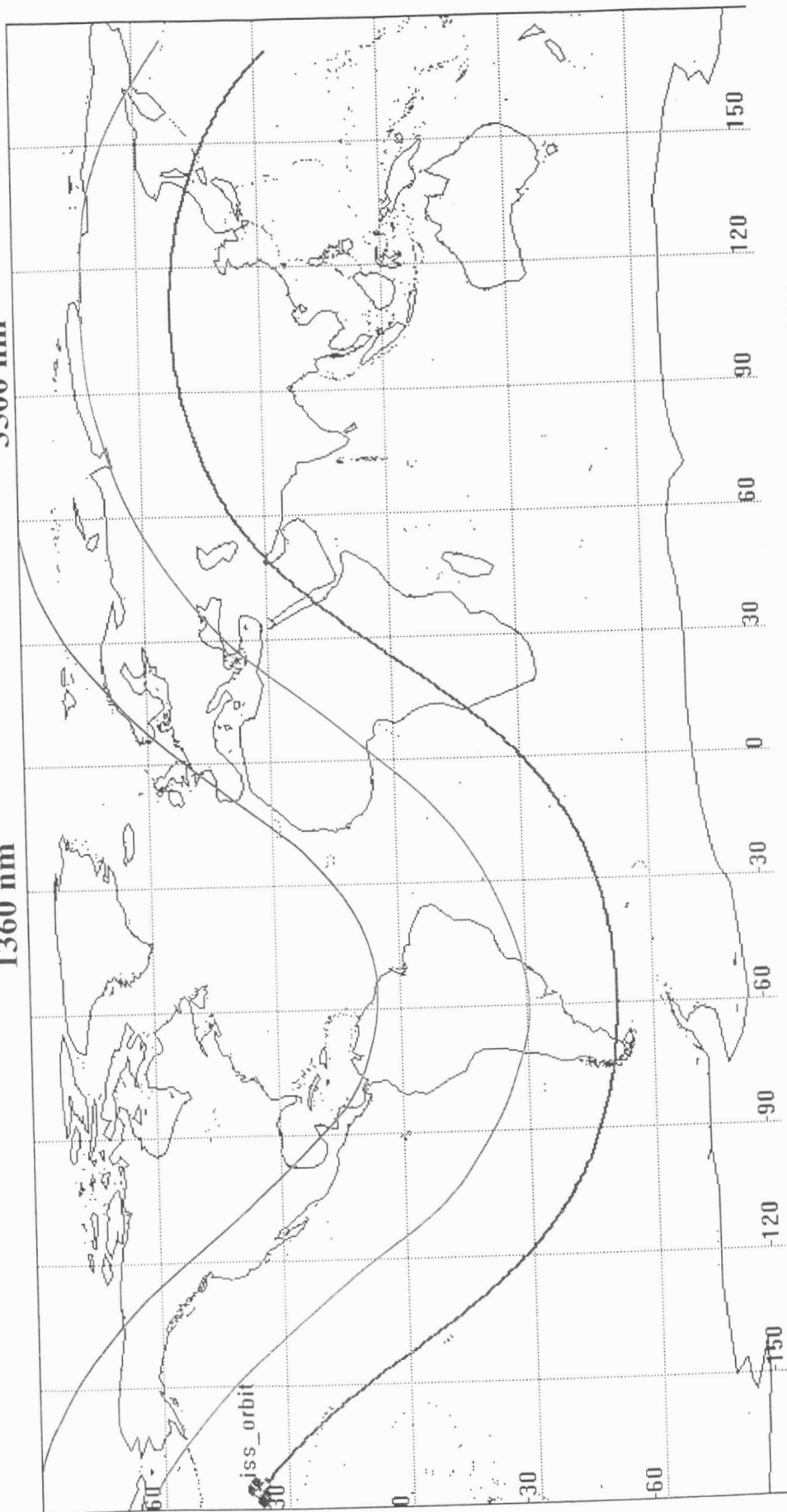


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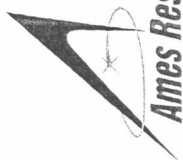


## ISS Ground Track vs. Cross Range

— ISS Ground Track      — HL-20 Max Cross-Range 1360 nm      — Sharp-V5 Max Cross-Range 3500 nm



***Significant Cross-Range advantages with SHARP-V5***

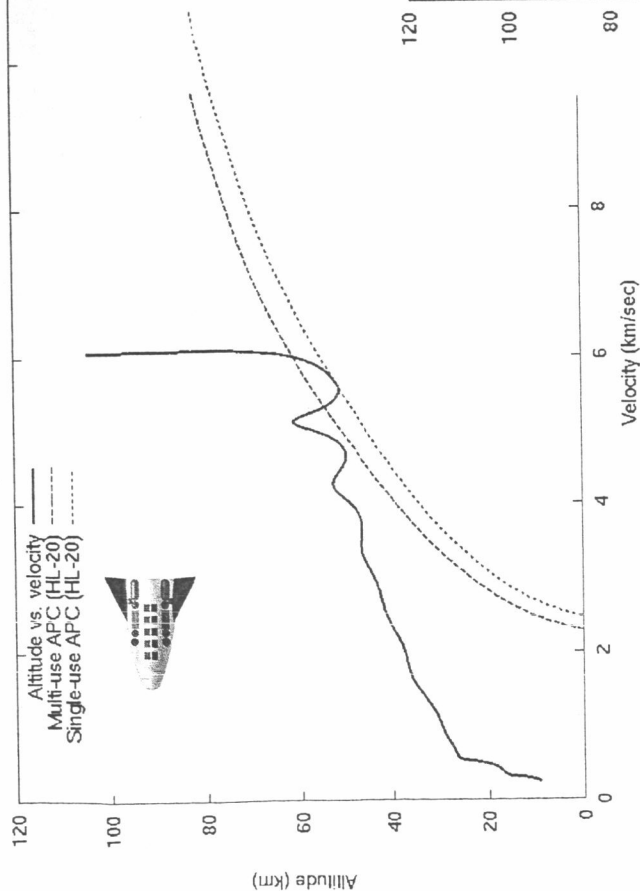


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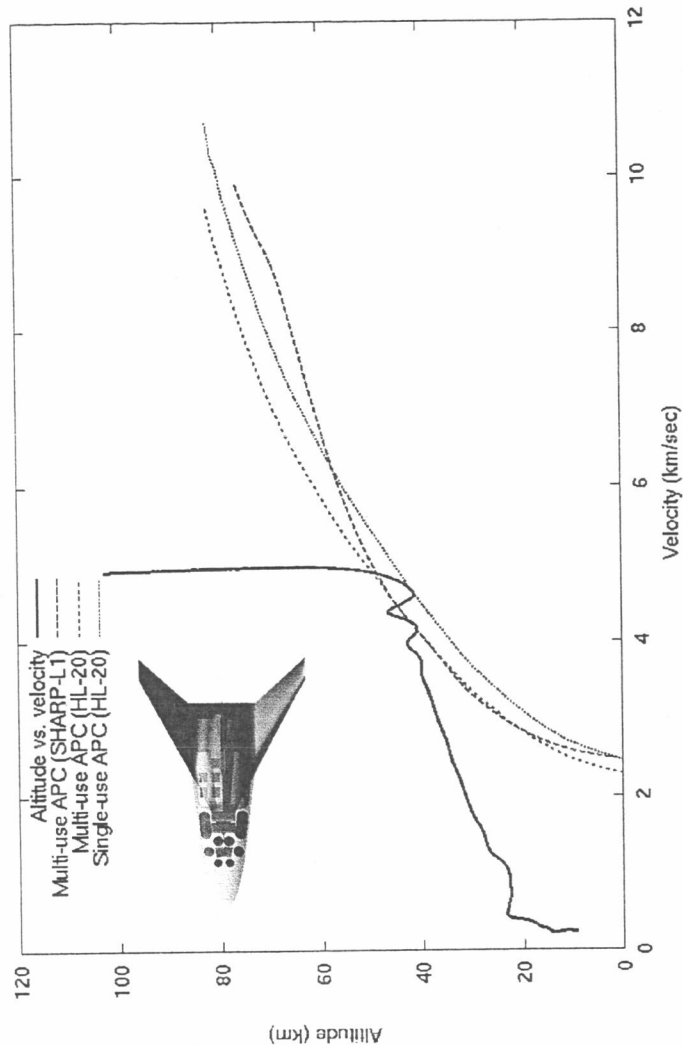
# Ascent Abort Trajectories Optimization



HL-20 Ascent Abort to Cape Verde at 30,000 ft. Tmin = 389.34 sec (08/31/00)



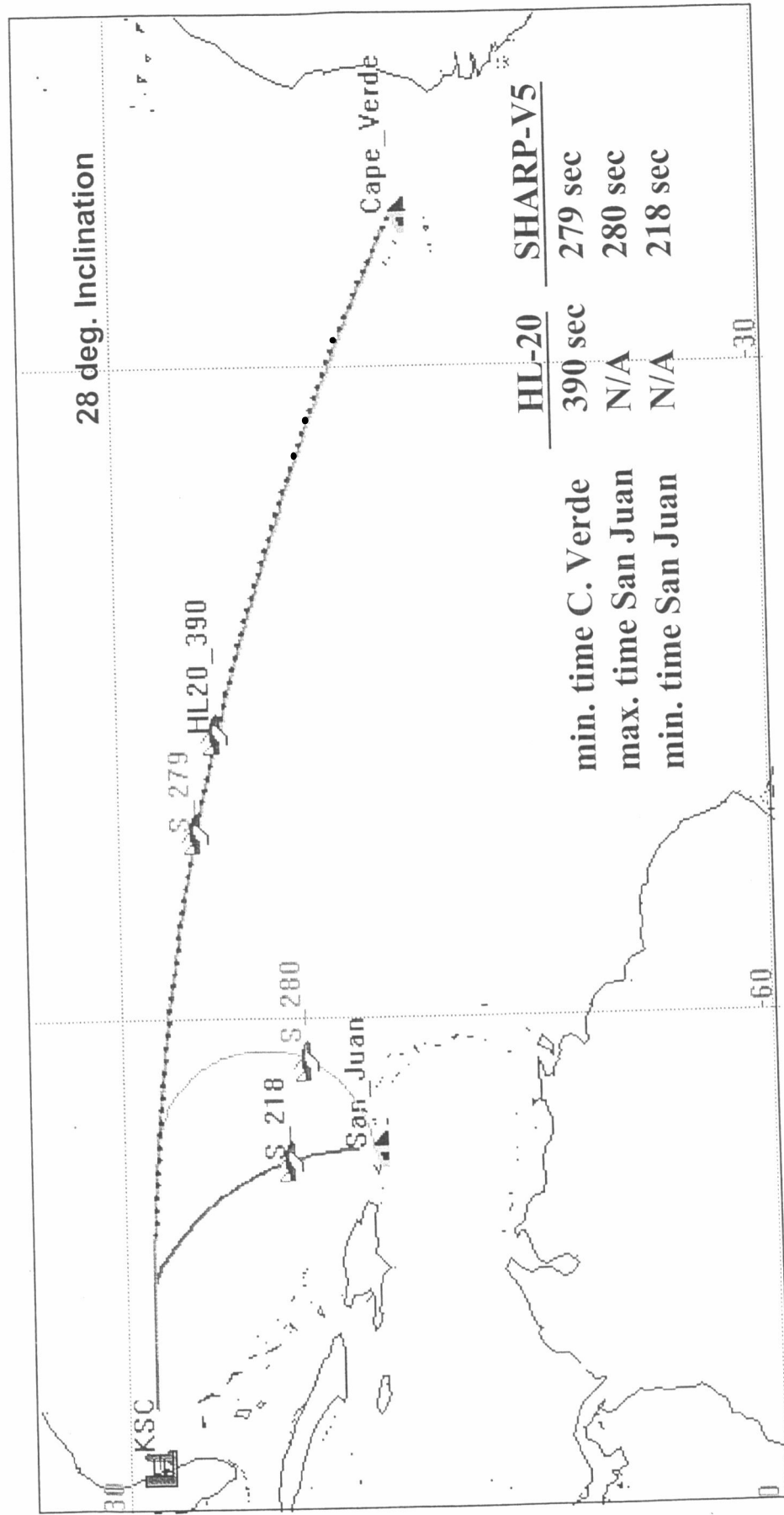
SHARP-V5 Ascent Abort to Cape Verde at 30,000 ft. Tmin = 279.02 sec (08/29/00)





# Abort Trajectories HL-20 and SHARP-V5

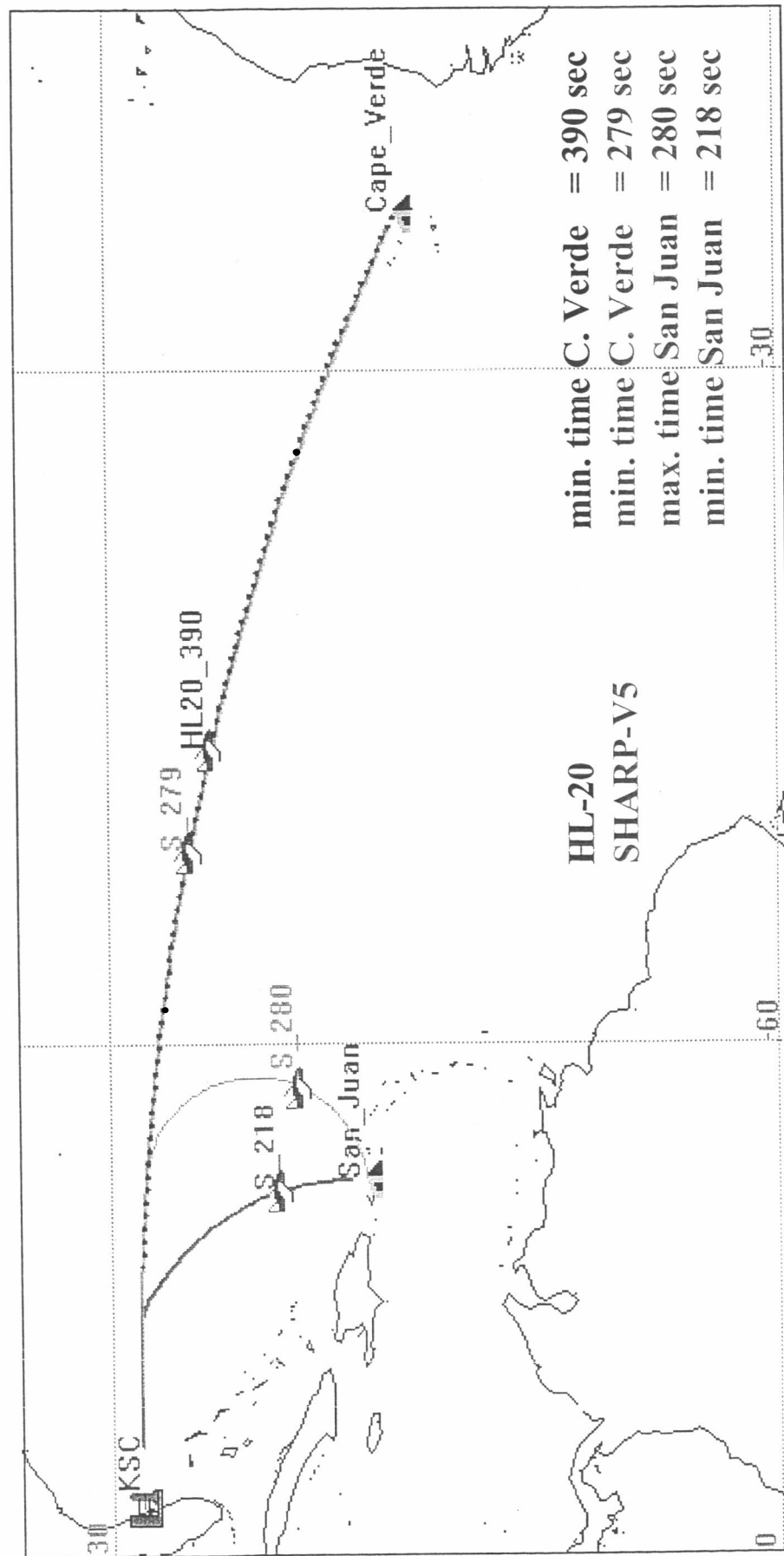
Ames Research Center

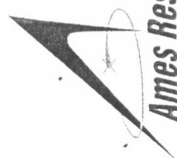


*Significant Abort advantages with SHARP-V5*

# Abort Trajectories HL-20 and SHARP-V5

28 deg. Inclination

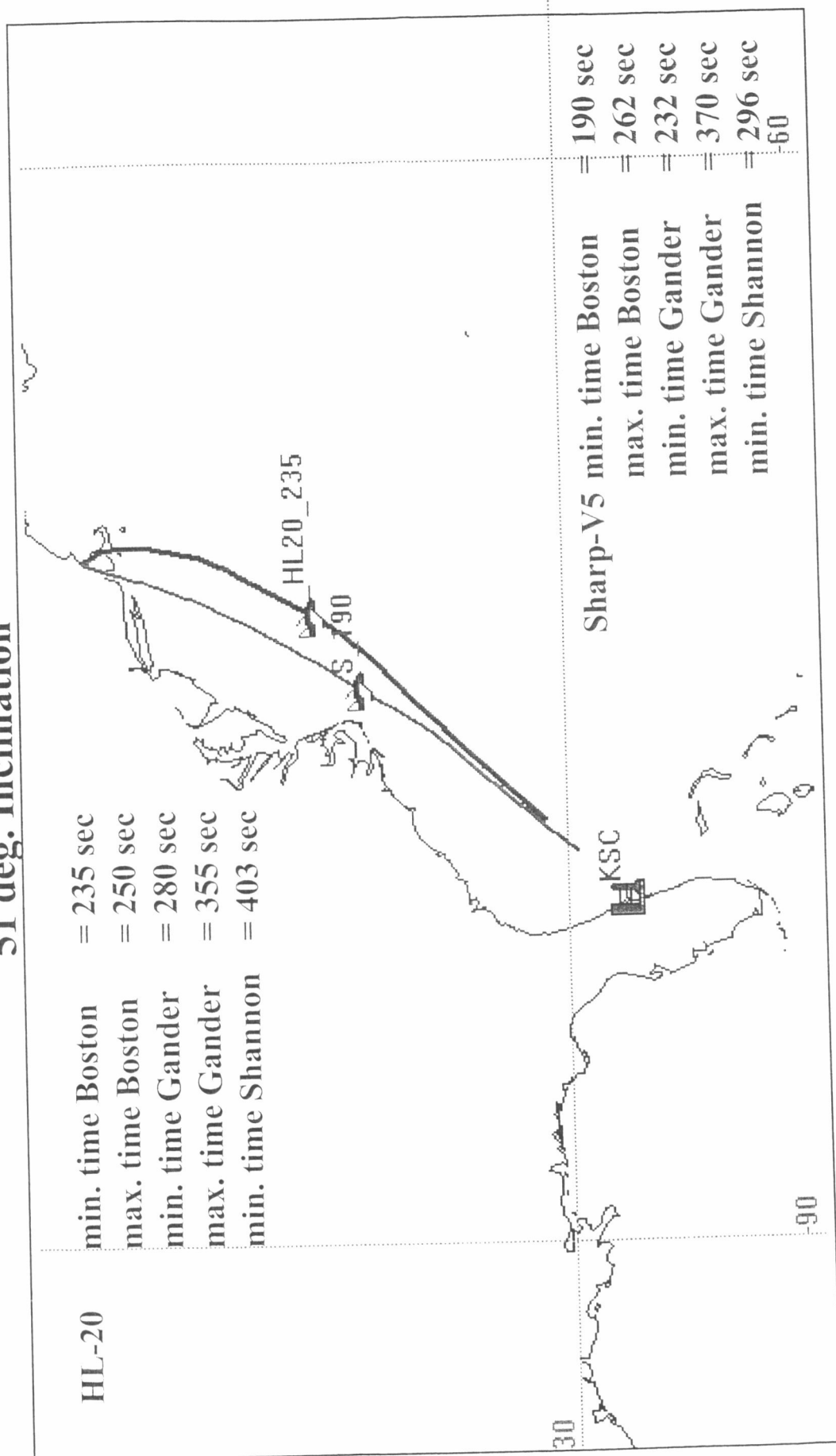


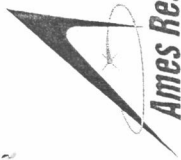


# Abort Trajectories HL-20 and SHARP-V5



## 51 deg. Inclination





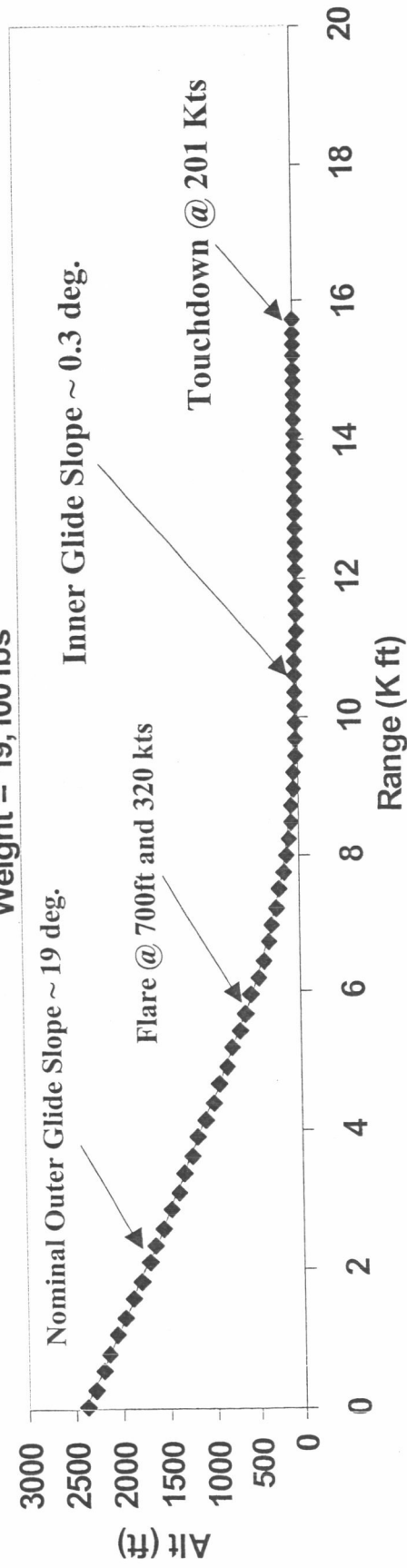
Ames Research Center

# Landing Simulations



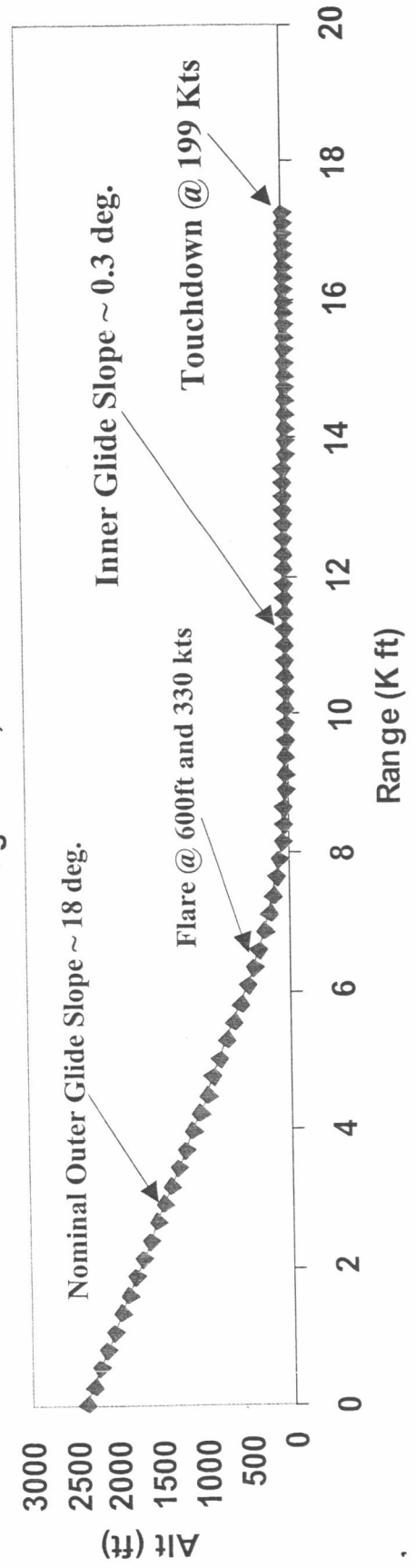
## Nominal HL-20 Landing Flare Simulation

Weight = 19,100 lbs



## Nominal SHARP-V5 Landing Flare Simulation

Weight = 25,500 lbs

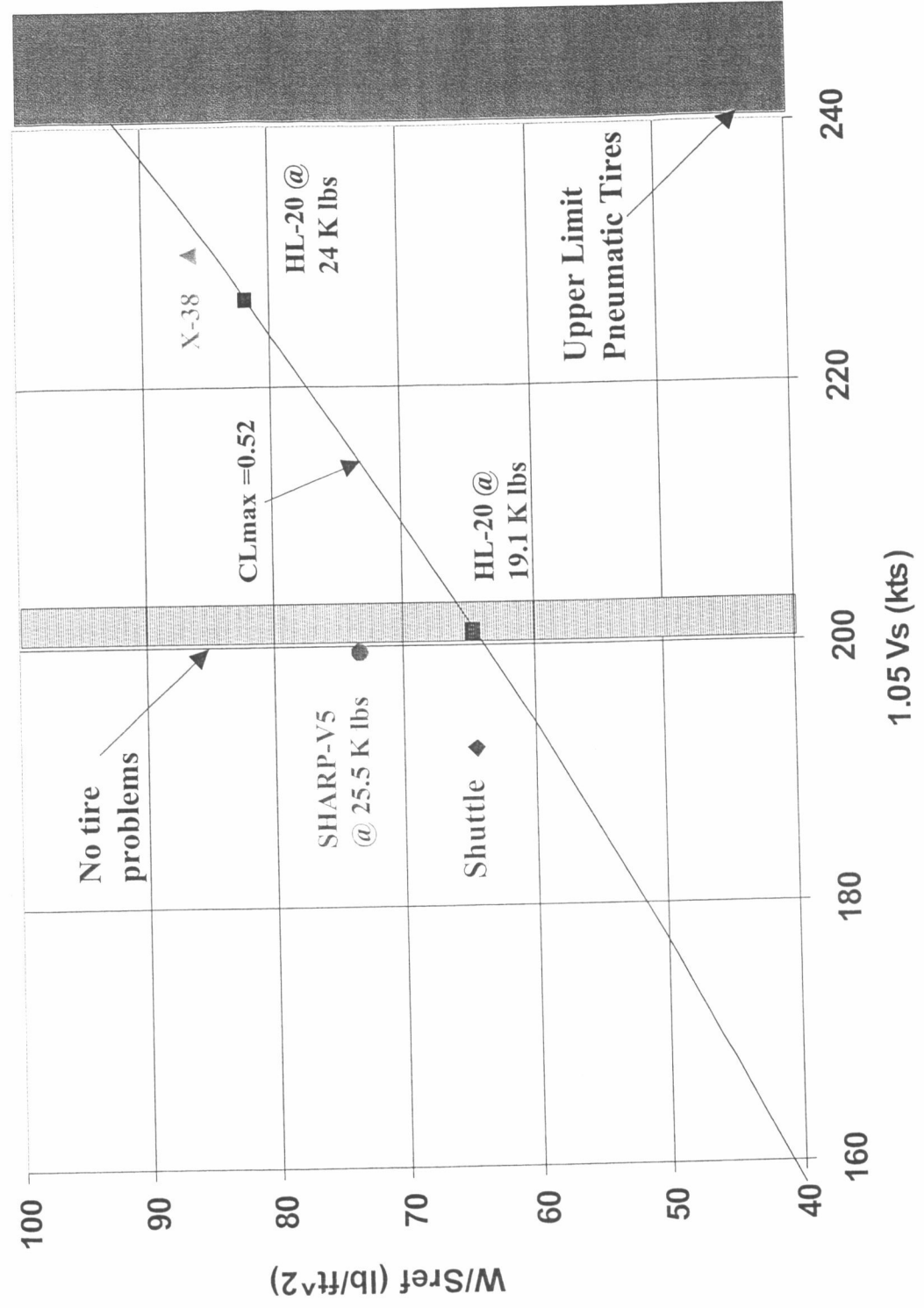




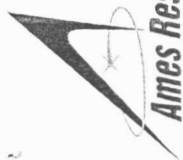
# Landing Simulations



Wing Loading and CLmax Affects on Landing Speed



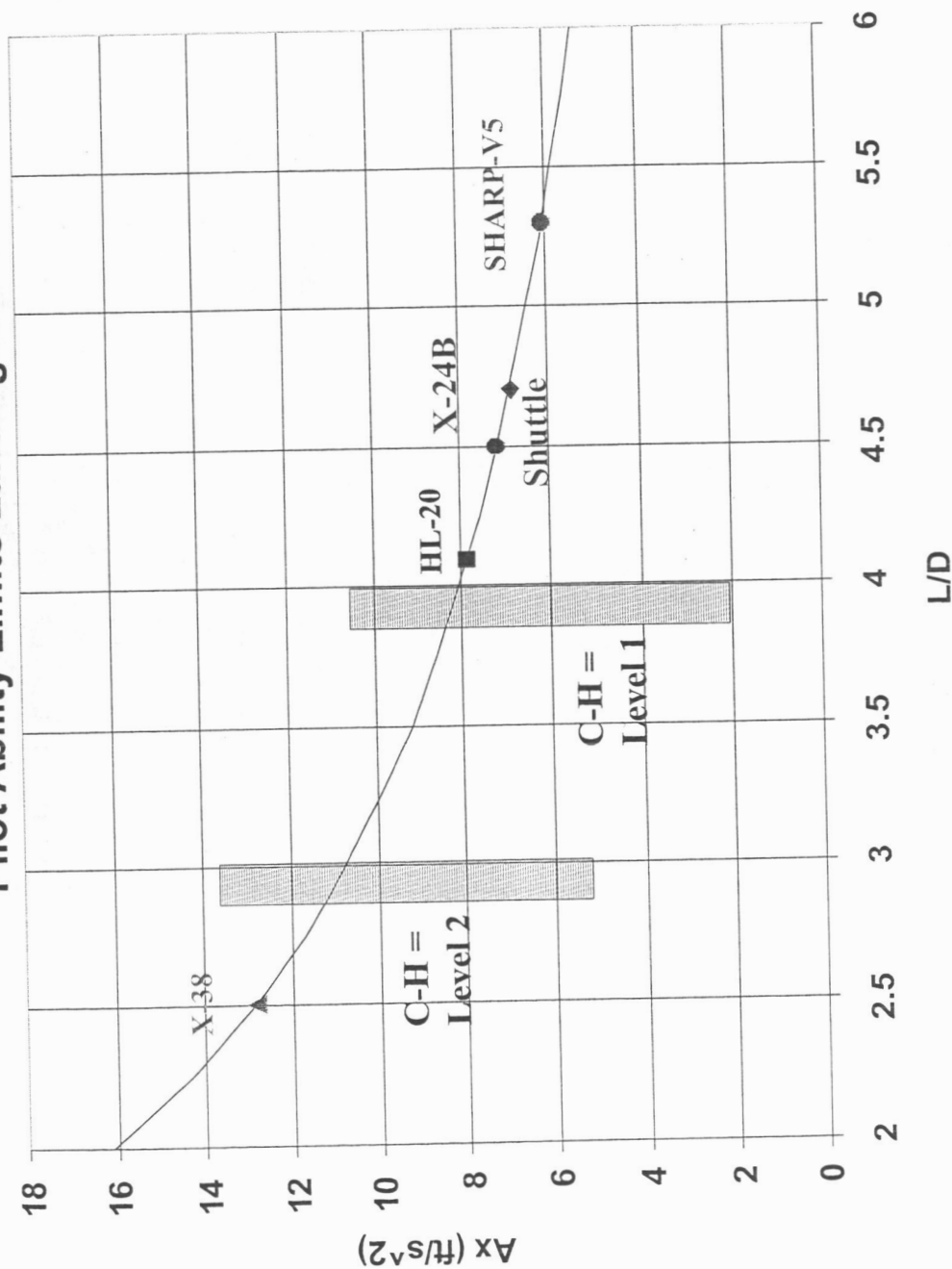




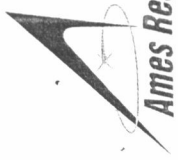
# Landing Simulations



L/D Affects Landing Task Through Longitudinal Deceleration  
Pilot Ability Limits Landing L/D



*Significant Landing advantages with SHARP-V5*



## Summary of Ames Sharp CTV Architecture Study



- Ames CTV study shows a viable closed vehicle for SHARP V-5:
  - Significant safety and performance benefits shown for a SHARP-V5 using UHTC's versus the HL-20 with Shuttle era materials
    - *Improved abort, cross range and landing capabilities*
  - Cross range benefits put larger heat load demand on acreage TPS - research warranted for thinner/lighter materials
- Results Published as AIAA Papers
  - Systems Analysis & Conceptual Design (AIAA 2001-2887)
  - Aerothermal Performance Constraints (AIAA 2001-2886)
  - Trajectory Analysis (AIAA 2001-2885)
  - Low Speed Aerodynamics & Landing (AIAA 2001-2888)



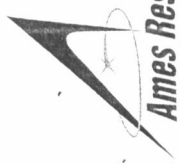
# VF-RITE Introduction



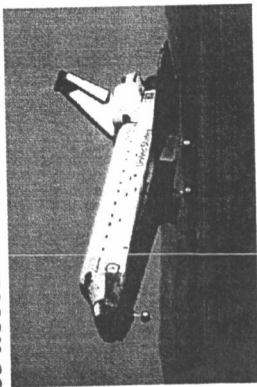
## Virtual Flight Rapid Integration Test Environment

### Vision Statement:

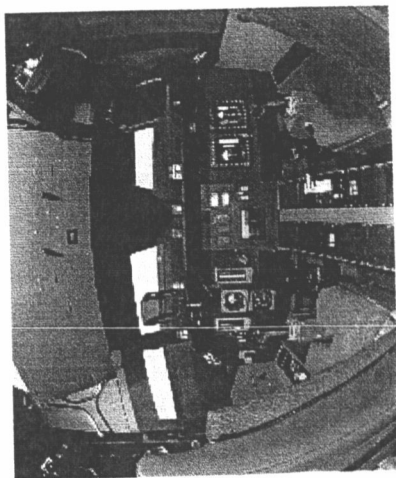
**Merge advanced Information Technologies to facilitate flight simulation as an integral part of the design process and return and employ the acquired knowledge base for the improvement of individual/total systems.**



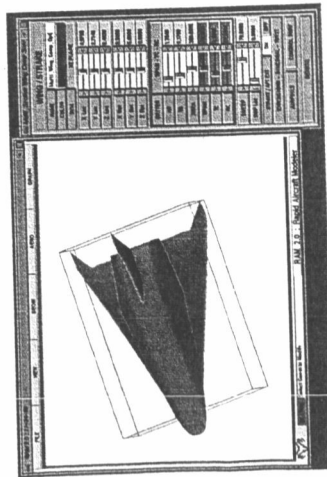
Ames Research Center



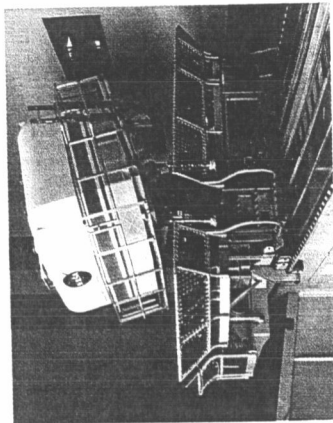
Flight Data



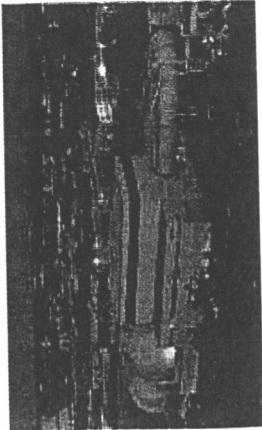
Aircraft Cockpit



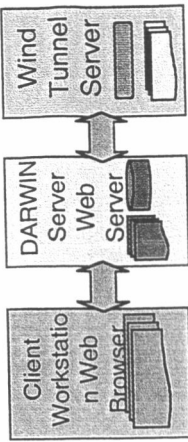
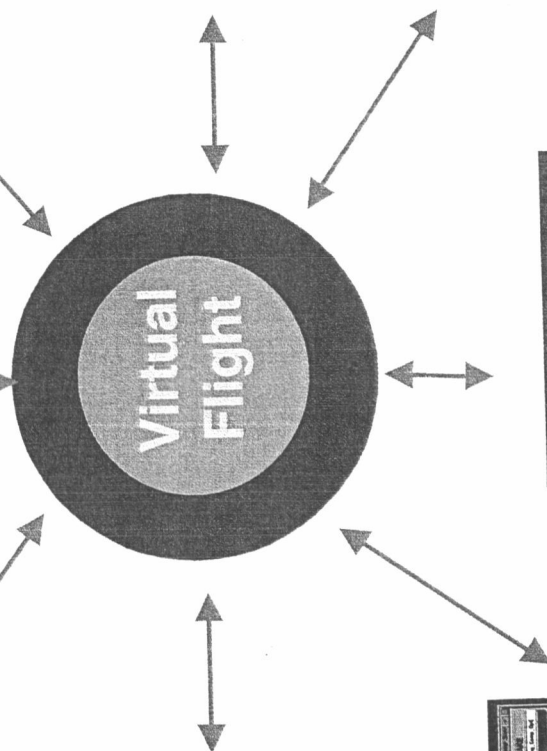
Design Optimization Tools



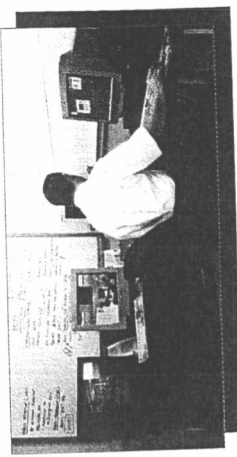
Flight Simulation



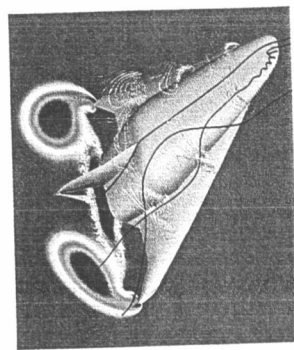
Wind-Tunnel



Data Transfer

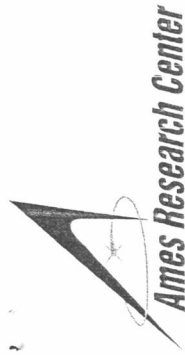


VLAB



CFD





# VF-RITE Goal and Objectives

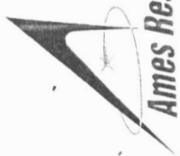


## Goal

To develop and apply design and optimization tools, data generation methods, and real-time piloted simulation evaluations to a preliminary design case study: Sharp Crew Transfer Vehicle (CTV)

## Objectives

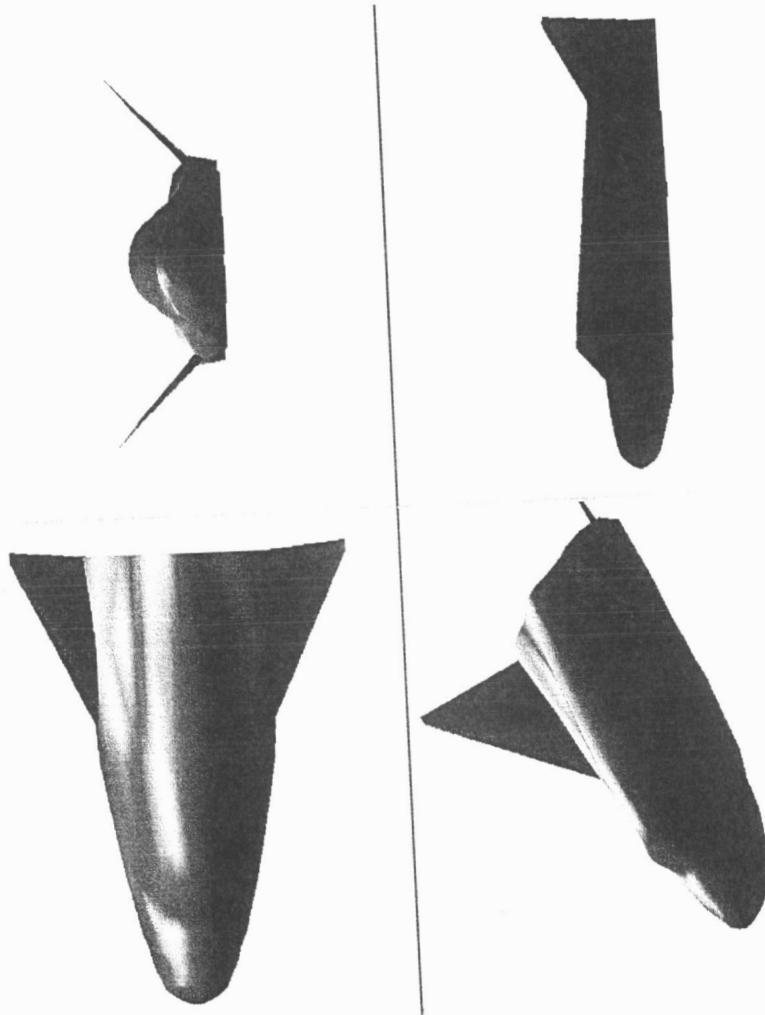
- Develop rapid, iterative design process to be applied to a preliminary design for a re-entry space vehicle
- Meet all mission requirements for a CTV design
- Achieve optimal performance (aerodynamic, aerothermal, subsonic handling qualities, etc.) in all flight regimes
- Evaluate stability, control and handling qualities of Sharp CTV through real-time piloted simulations in NASA Ames Vertical Motion Simulator facility
- Apply return knowledge to design team to rapidly re-design CTV and obtain pilot evaluations on new design



## VF-RITE Goal and Objectives (cont.)



- Use HL-20 blunt-body design, developed by NASA Langley with same mission requirements, to validate methods and make comparisons



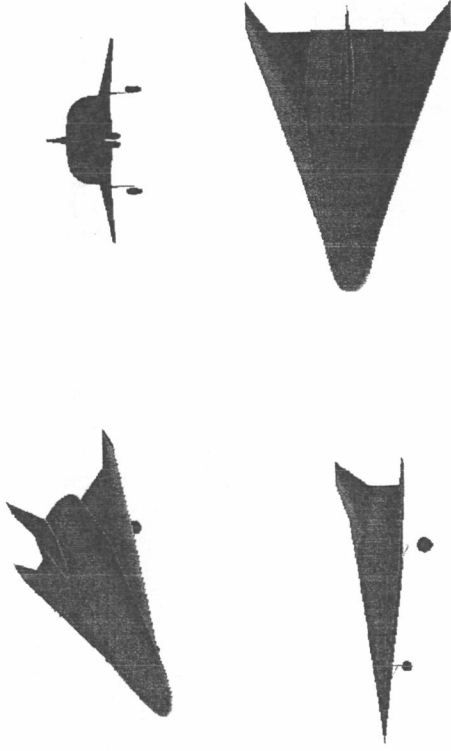


# Crew Transfer Vehicle



## Mission Requirements

- Reusable vehicle
- Launch on an expendable launch vehicle
- Accommodations for 8 passengers and crew
- Orbit-to-orbit transfer
- Rendezvous with Station
- Piloted and automated entry and runway landing capability



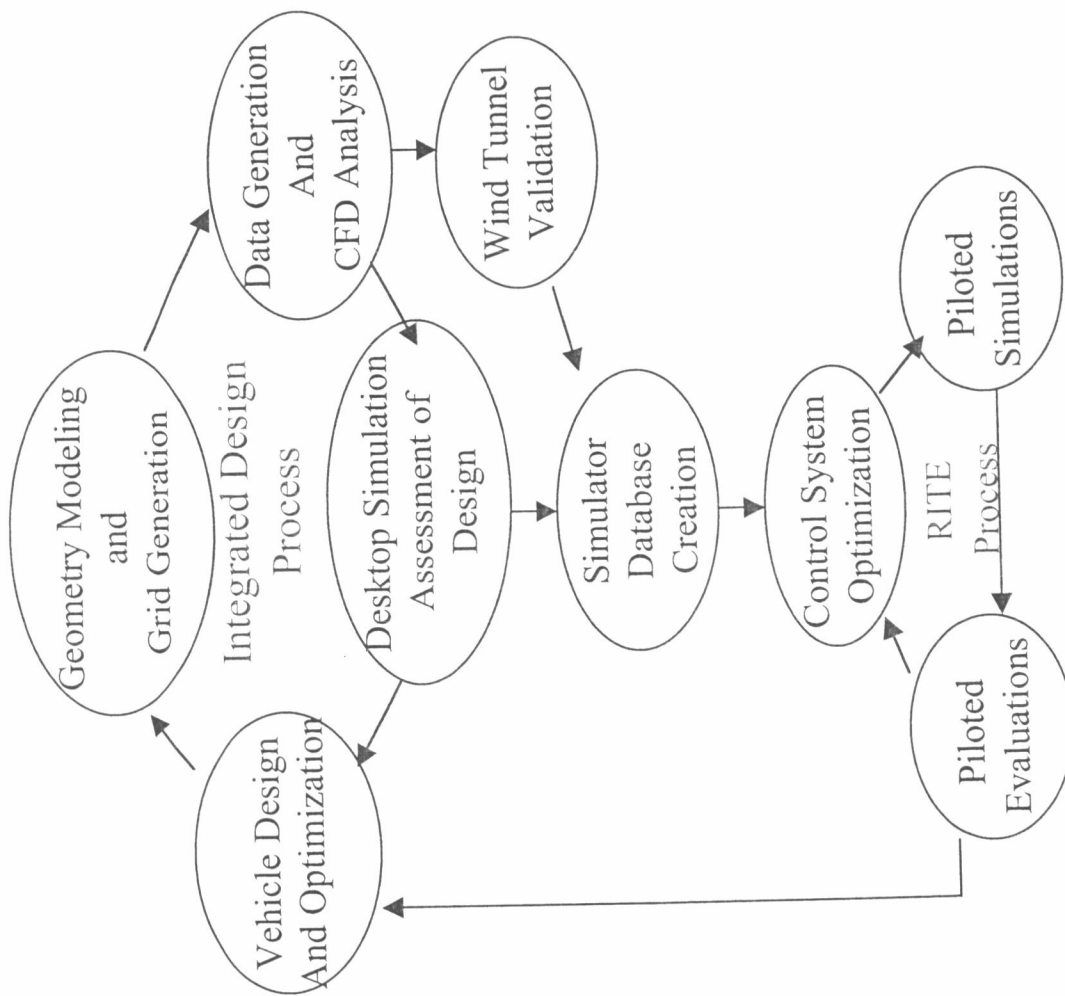
## Design Constraints

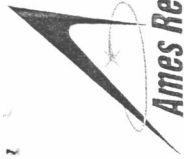
- Use of Ultra High Temperature Ceramics (UHTCs) developed at NASA Ames to enable use of sharp leading edges
- Re-Entry weight less than 26000 lbs.
- Hypersonic L/D greater than 2
- Cross range capability greater than 2000 nm
- Subsonic L/D greater than 4

CTV-v7 or CV0



# Integrated Design and RITE Process





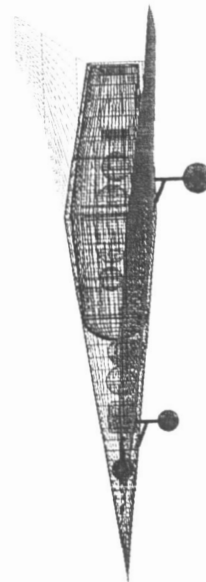
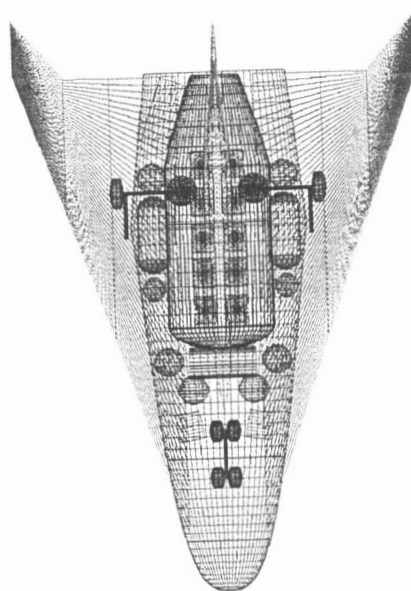
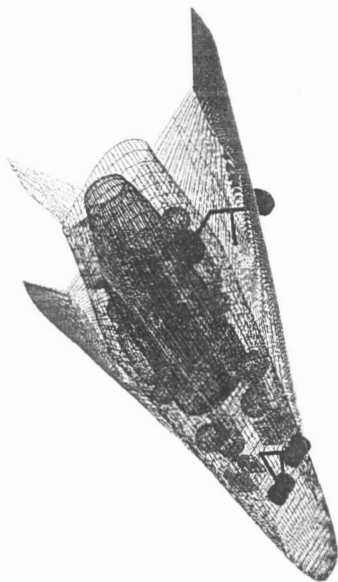
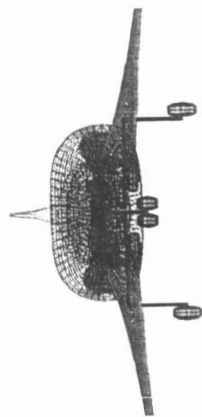
# Vehicle Design and Optimization

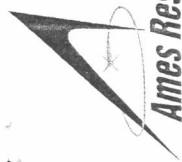


- Aerodynamic shape optimization technique was developed by coupling:
  - AIRPLANE, an Euler unstructured-tetrahedral-grid-based CFD code
  - QNMDIF, an unconstrained quasi-Newton finite-difference optimization method
- Aerodynamic performance was optimized by varying selected geometry design variables
  - Wing leading and trailing edge twist
  - Wing dihedral
  - Camber
  - Elevator deflection angle
  - Fuselage geometry variables
- Manual design efforts were also used periodically
- Design objective
  - Trim at Mach 6.0 and  $\alpha = 13^\circ$
  - Trim at Mach 0.3 and  $\alpha = 9^\circ$
  - Achieve best L/D at 2 conditions simultaneously
- Ames CTV-v7 was used as baseline vehicle and renamed as Concept Vehicle 0 or CV0
- Subsequent configurations were named CV1 through CV5



# SHARP CTV, v7





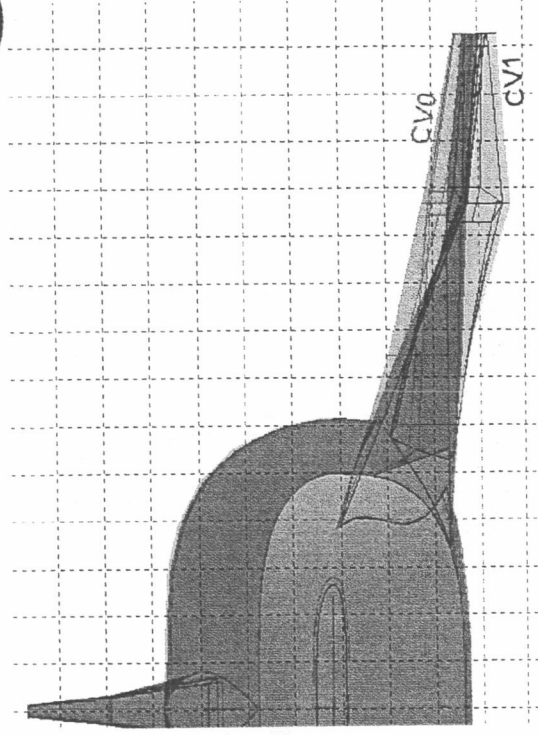
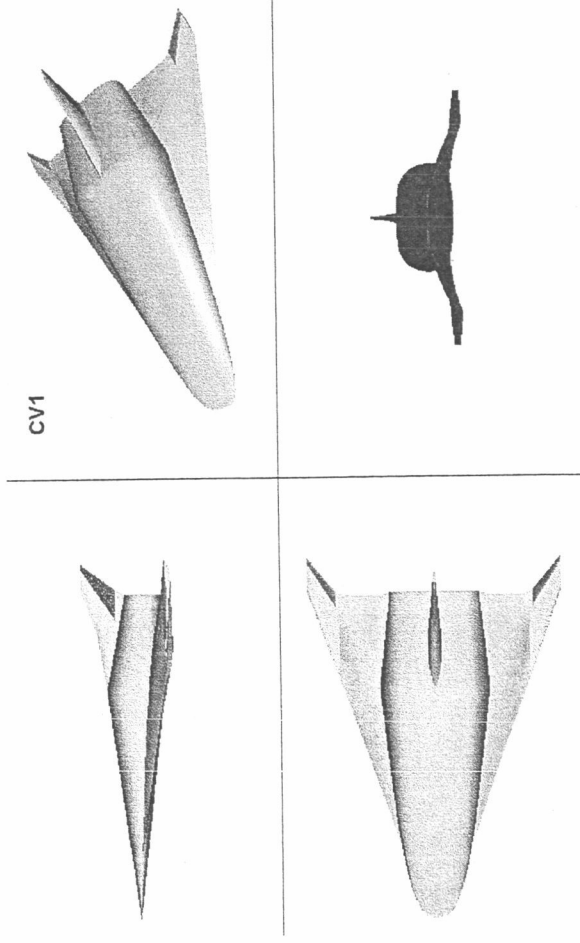
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# Concept Vehicle 1



## Design Objective

- Modify longitudinal stability to improve trim conditions
- Simultaneously improve performance of vehicle at both design points

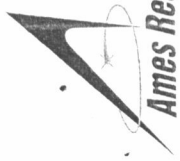


## Design Variables

- Wing twist about trailing edge
- Camber
- Elevator (inboard wing flap)

## Optimization Results

- Wing twist =  $-12.4^\circ$
- Elevator up =  $0.05^\circ$  for Mach 0.3
- Elevator down =  $5.2^\circ$  for Mach 6.0



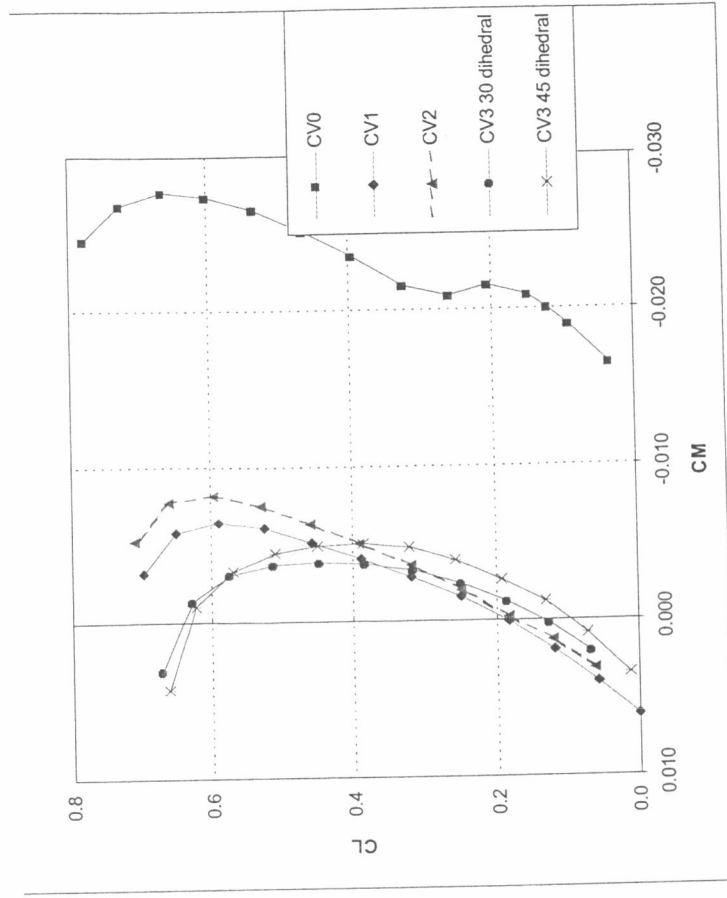
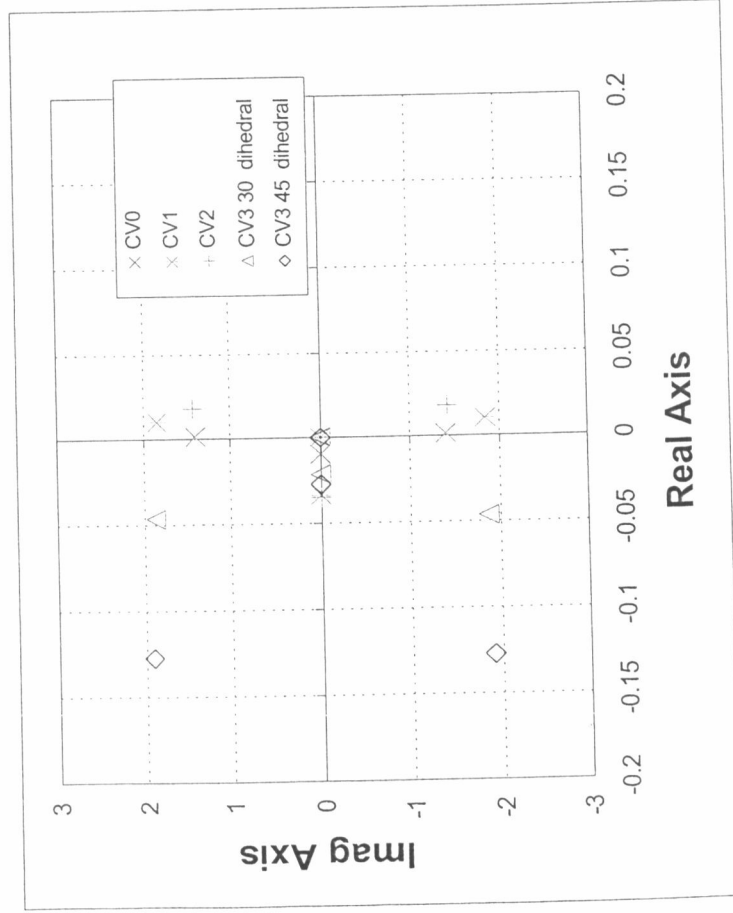
# Concept Vehicle 3

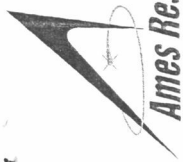


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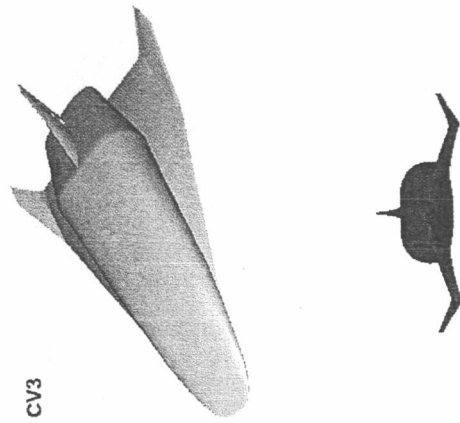
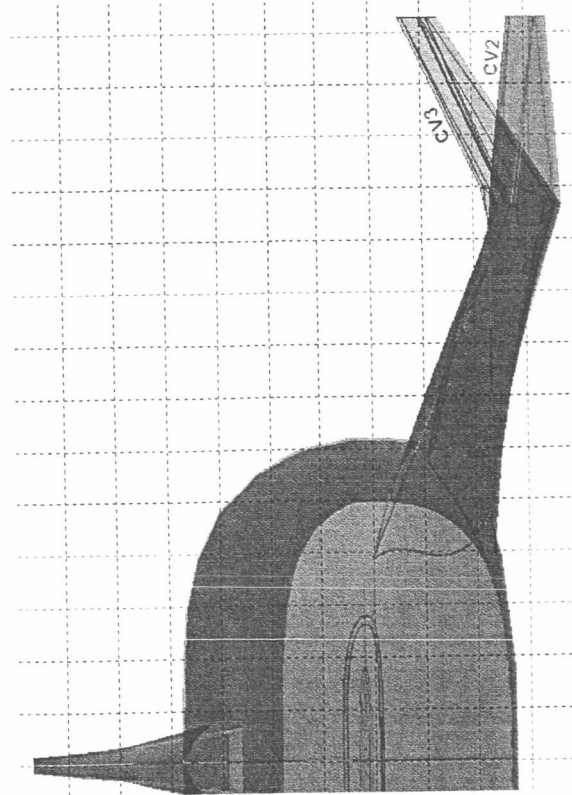
## Design Objective

- Add wing dihedral to stabilize lateral-directional stability modes
- Simultaneously maintain or improve longitudinal stability



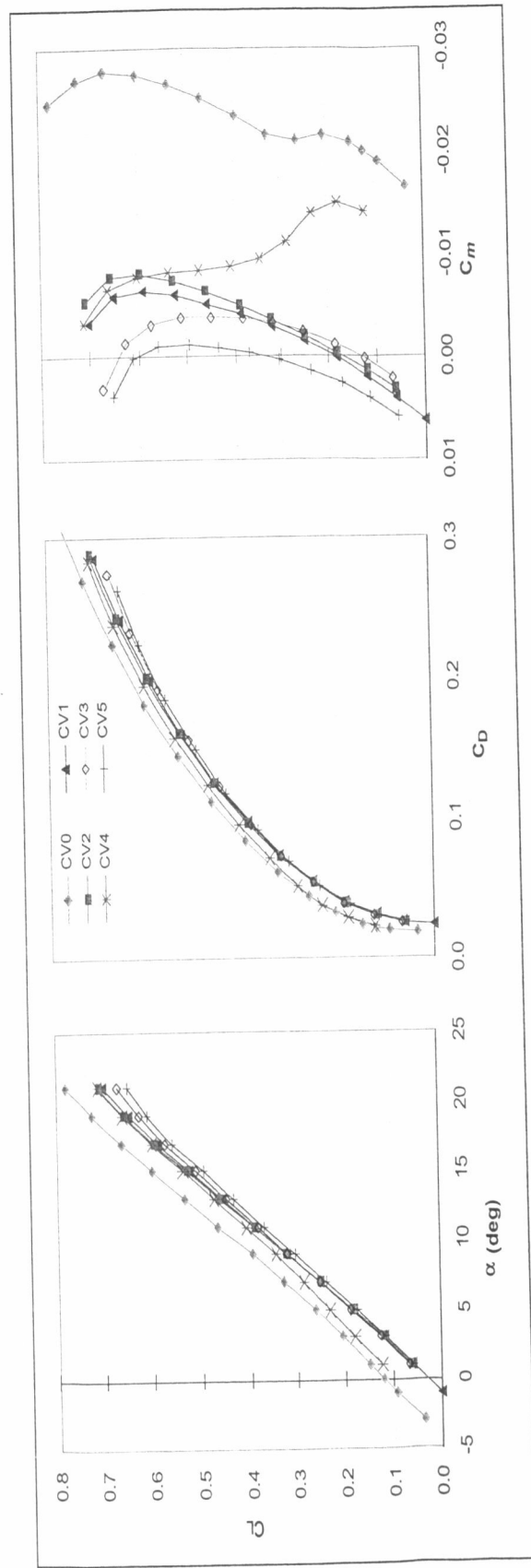


# Concept Vehicle 3

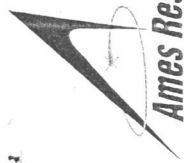




# Mach 0.3 AIRPLANE Results







## Low-Speed Wind-Tunnel Test



- Test conducted in NASA Ames Fluid Mechanics Lab 3-ft by 4-ft indraft wind tunnel
- Configurations tested: CV0 and CV2
- Models were fabricated using a stereo lithography technique for rapid delivery
- Moveable control surfaces
- 6-component force balance and 3-axis accelerometer used
- Data were taken at:
  - Mach number 0.11 and dynamic pressure 20 psf
  - Re 1.1 million based on body length of 22 in.
  - Angle of attack range was  $-3^{\circ}$  to  $22^{\circ}$
  - Sideslip range was 0 to  $5^{\circ}$

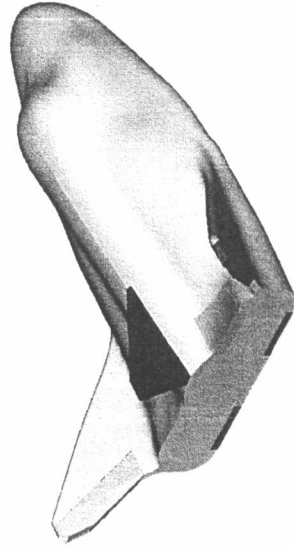


# Control System Design and Optimization

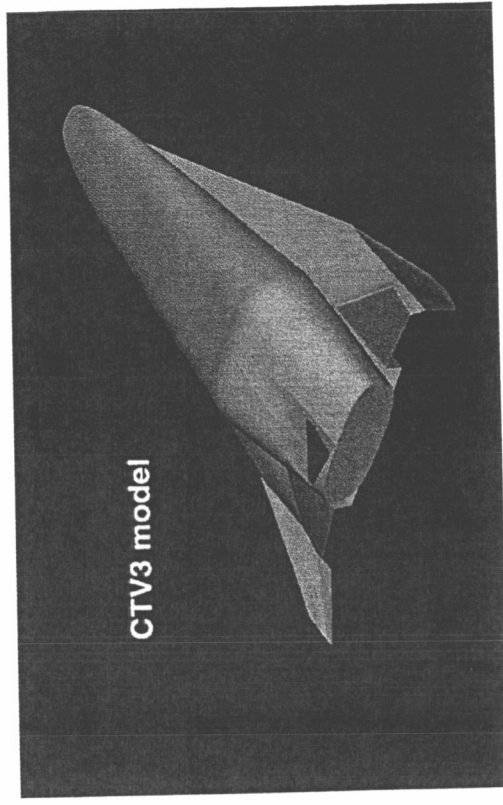


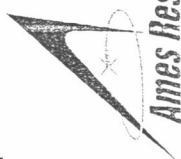
- HL-20 control system was used as starting point for CTV configuration
- Preliminary control system and linear aerodynamics model were developed
- Matlab and Simulink tools were used for development and initial evaluation
- Control system was modified to account for CTV control surfaces

HL20 model

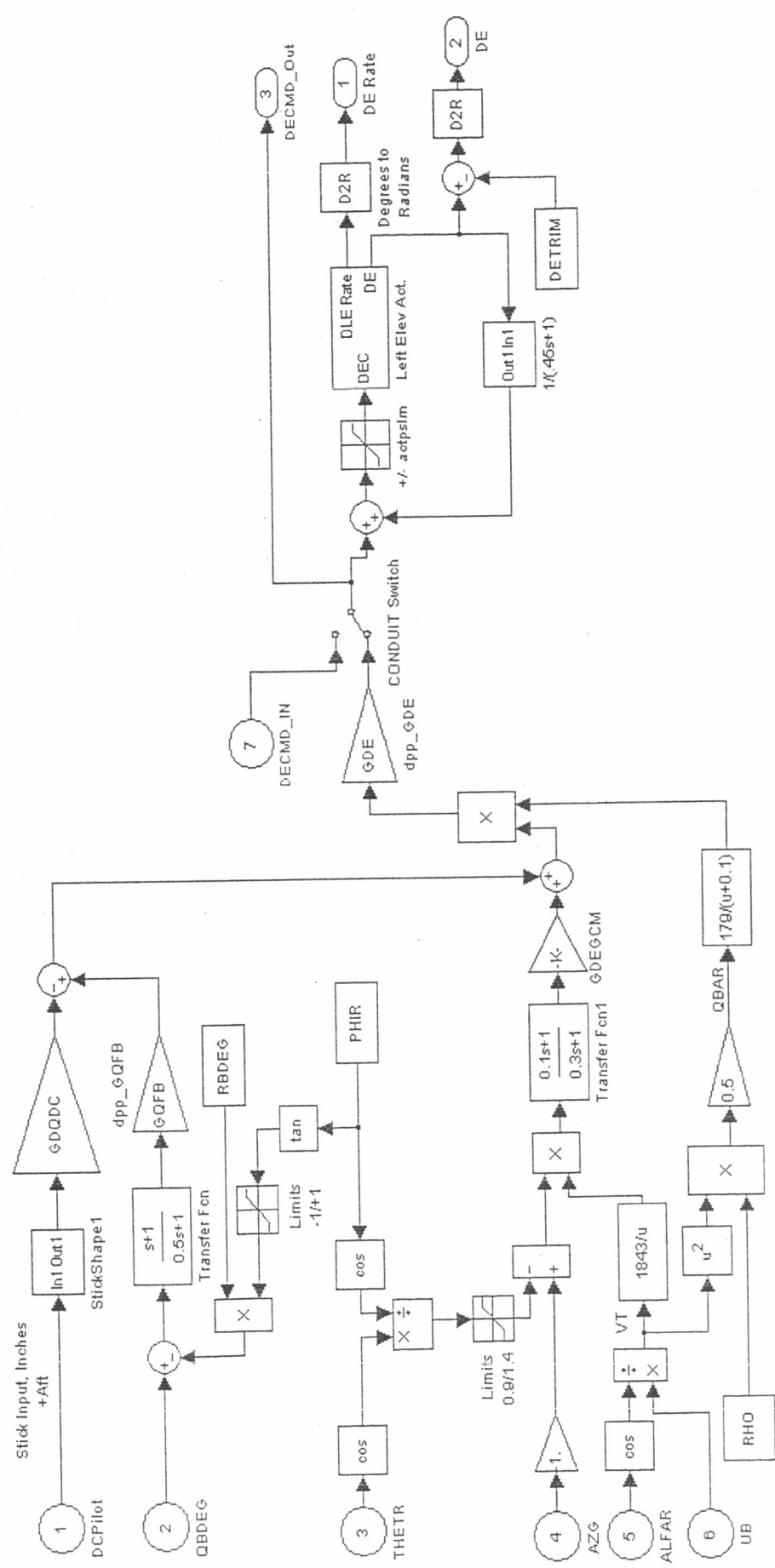


CTV3 model





# CTV Longitudinal Pitch Control Laws

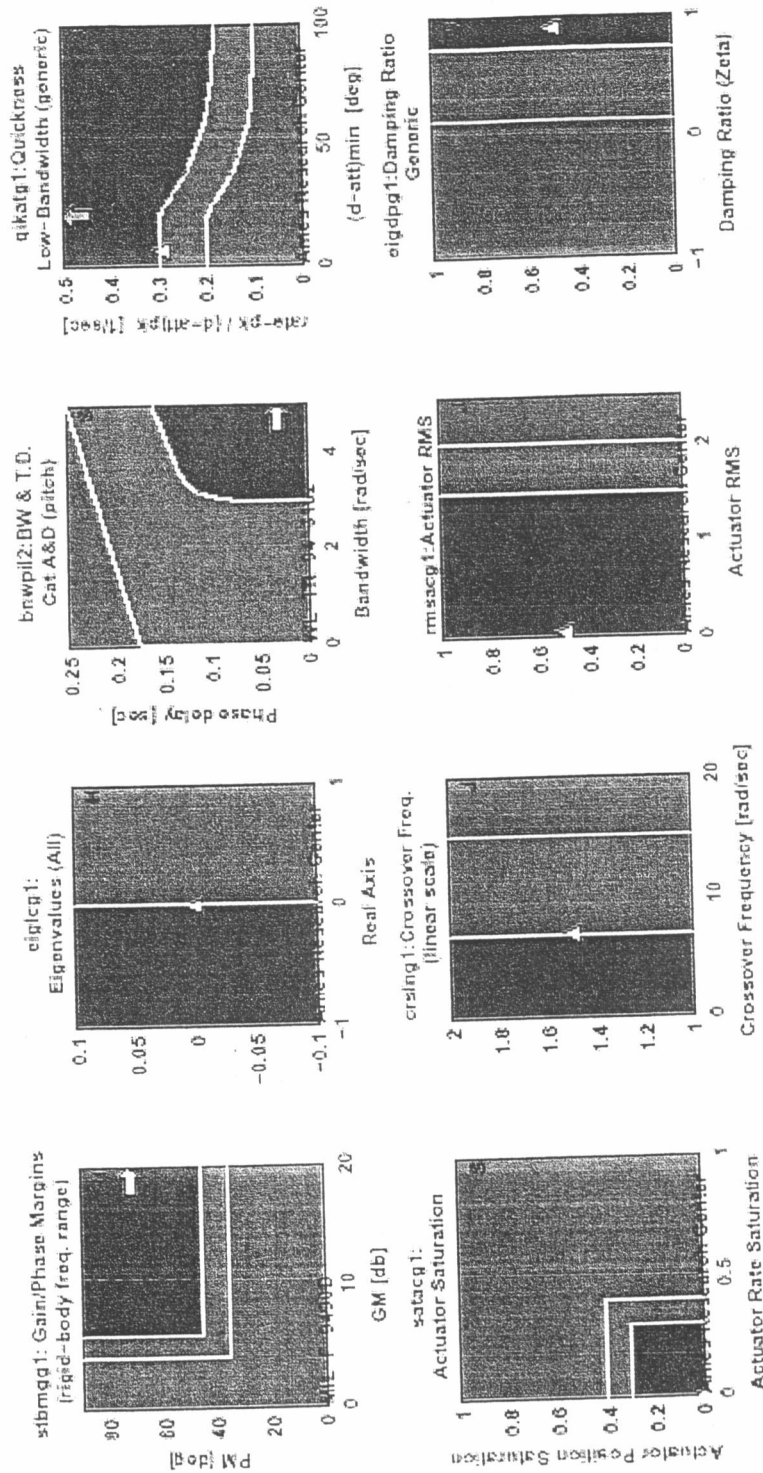


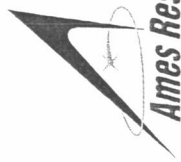


# Control System Optimization

Ames Research Center

- New control system gains were optimized for each new aerodynamics model using CONDUIT
- New longitudinal and lateral-directional specifications were defined to achieve Level 1 handling qualities



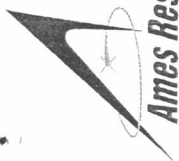


# VMS Simulation Experiment



## Objectives

- Evaluate HQs of SHARP CTVs for piloted tasks specified during approach and landing
- Use SSV simulation as baseline for comparison to SHARP CTV simulations
- Evaluate HQs for HL-20 simulation developed by NASA Langley for comparison to a blunt-body design with same mission requirements
- Evaluate HQs using Cooper-Harper ratings on 5 CTV configurations (CTV0 thru CTV4)
- Use pilot feedback and recommendations to re-design CTV for improved performance in handling qualities and/or aeroperformance
- Demonstrate capability to rapidly re-design configuration, re-generate aero model and obtain pilot evaluations on new design



# VMS Simulation Experiment

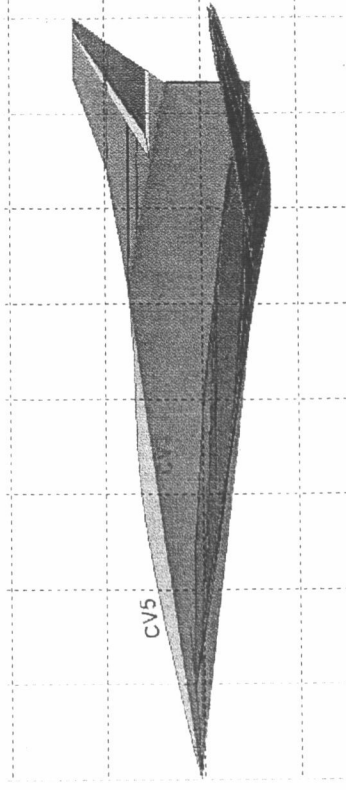


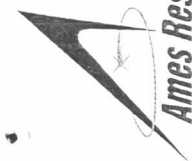
## Piloted Tasks

- Nominal approach and landings
  - Initiated at 10K ft.
  - HUD display was used
  - Land within specified criteria
- Crosswind approach and landings
  - Realistic wind models with turbulence used
  - 15 kts. tailwind and 20 kts. crosswind
- Lateral offset landings
  - Approximate 400 ft. offset used
  - 300 ft. altitude return to centerline
  - Aggressive maneuver to excite lateral-directional modes

# Rapid Redesign of CV5

- From pilot feedback and recommendations, new aerodynamics model was generated and implemented into sim
- Fuselage geometry variables were optimized to increase fuselage width and nose droop to improve pilot visibility
- Seven design variables were used including:
  - Wing twist about leading edge
  - Body leading and trailing droop
  - Forebody camber
  - Forebody upper surface thickness
- Optimization results
  - Nose moved up by 1.2%
  - Aft body drooped by 3.2%
  - Wing twist was 2.29°
  - Forebody thickness increased at 25% and reduced at 60% of forebody



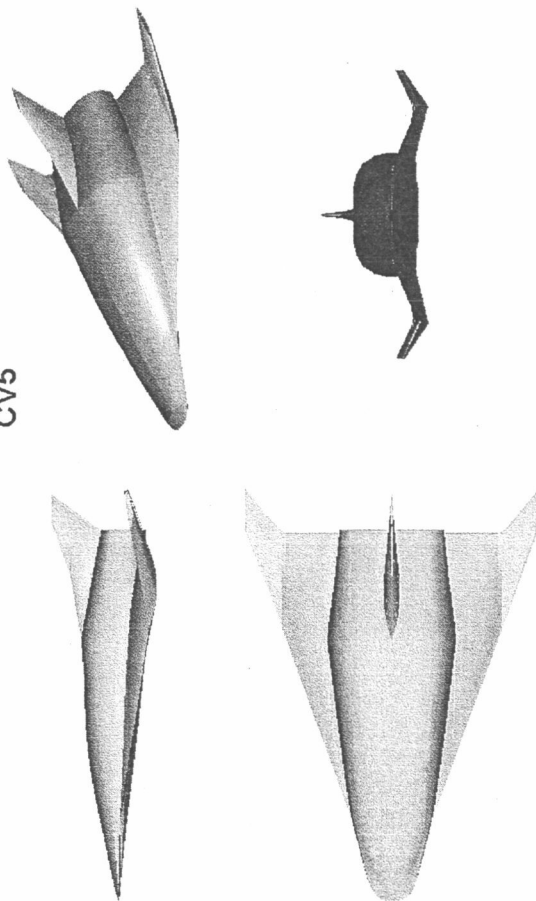


## Rapid Redesign of CV5



- New computational simulations (Euler) were run
- New aerodynamics database for CV5 was generated
- New control system gains were optimized
- New pilot evaluations were obtained
- Rapid redesign process was completed within 4 weeks

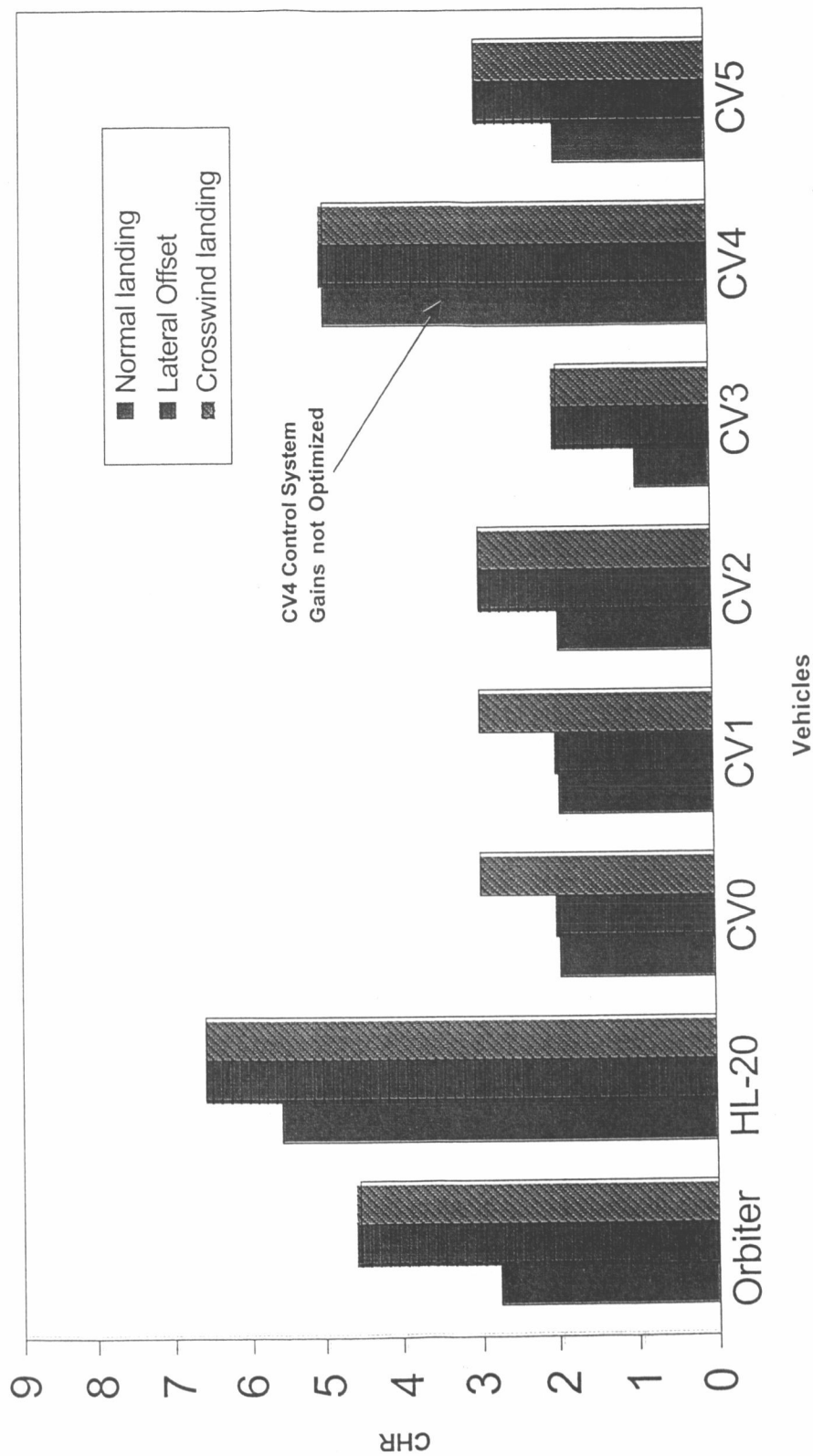
CV5

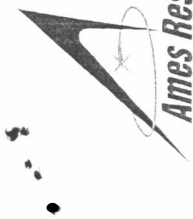






# Cooper-Harper Ratings





## Summary of VF-RITE Task on Sharp CTV



- Virtual Flight RITE project demonstrated capability to integrate CFD, flight and wind-tunnel data into a simulation
- Design of a Sharp Crew Transfer Vehicle concept was developed using integrated design process
- Aerodynamic models for 6 CTV configurations (CV0 through CV5) were developed
- Low-speed wind-tunnel test was conducted to validate CFD results
- Simulation experiment was conducted to evaluate low-speed handling qualities in approach and landing phase
- Control system optimization technique was developed for rapid optimization of control system gains
- Six astronaut pilots evaluated each configuration using Cooper-Harper ratings
- Using pilot feedback, a new configuration was developed and cycled back through the simulation evaluation
- AIAA 2002-4881



## Conclusions & Future Work



- A Closed SHARP Class CTV has been presented which shows
  - Improved re-entry performance compared to blunt vehicle concepts
  - Improved Ascent Abort Safety compared to blunt vehicle concepts
  - Similar Landing Performance to blunt vehicle concepts
- A Better Understanding of SHARP Class Vehicles has been Established
  - Drivers for Using UHTC are Established
  - Understanding of drivers for UHTC APC's
- There remains the need to perform a continued and more in depth study
  - Structure & UHTC TPS Integration
  - Cost , Operations, Safety & Reliability
  - RTLS, ATO, Landing Performance, Ascent Stack Stability ....
- NASA and Industry has shown great interest on continued work
  - 2nd Gen Leader/Follower Concepts and 2nd Gen NRA